A Conceptual Model for Eight-Hour Ozone Exceedances in Houston, Texas

Part II: Eight-Hour Ozone Exceedances in the Houston-Galveston Metropolitan Area

John W. Nielsen-Gammon, James Tobin, and Andrew McNeel

Center for Atmospheric Chemistry and the Environment

Texas A&M University

January 29, 2005

The preparation of this report is based on work supported by the State of Texas through a Contract from the Houston Advanced Research Center, Texas Environmental Research Consortium and the Texas Commission on Environmental Quality.

Contact information:

John W. Nielsen-Gammon

3150 TAMUS

Texas A&M University

College Station, TX 77843-3150

n-g@tamu.edu

979-862-2248

Table of Contents

Executive Summary: Findings and Recommendations

Key findings and recommendations of general interest are in **boldface.**

From Chapter 2:

1. Background ozone may be defined as the lowest 8-h maximum ozone level on a given day within a region. (page 19)

2. When estimating background ozone for Houston, certain monitors with anomalously low ozone levels must be excluded. (page 19-21)

3. Annual variations in background ozone levels in Houston have a double peak, with high levels in the spring and late summer/early fall and low levels in early winter and early summer. (page 21)

4. The local contribution may be defined as the difference between the background ozone on a given day and the highest 8-h average on that day. (page 21)

5. In Houston, the highest local contributions occur in summer and the smallest occur in winter. (page 21)

6. The 8-h maximum ozone in Houston is a combination of these two annual cycles, resulting in a primary peak in August/September and a secondary, broader peak in May. (page 21)

7. The daily average 8-h maximum ozone in Houston at the August/September peak is 0.089 ppmv, which exceeds the 8-h ozone standard. (page 21)

8. Unlike other parts of central and eastern Texas, average local contributions to 8-h ozone in Houston during the summer are as large as background ozone concentrations. (page 22)

<u>From Chapter 3:</u>

9. 8-h ozone exceedances occur about 10 times per year each in August and September and about 20 times per year during the period April-July. (page 24)

10. The average annual number of 8-h ozone exceedances at the various monitors ranges from 4 per year to 18 per year. (page 26)

11. Because some ozone monitors in Houston are strongly influenced by instrumental or local effects, it is not possible to determine the true spatial distribution of high levels of ozone within Houston. (page 28)

12. Efforts should be made to determine the true cause of the systematic station-to-station variations in ozone concentration. (page 28)

<u>From Chapter 4:</u>

13. The highest 8-h design value for Houston peaked at 0.118 ppmv in 1998 and has fallen every year since then. (page 30)

14. The current (2002-2004) ozone design value for Houston is 0.102 ppmv, at station C53 (Bayland Park). (page 30)

15. A downward trend in design values is found at almost all monitors. (page 30)

16. The characteristics of high ozone days may be determined by compiling statistics on the third through sixth highest 8-h days each year at each monitor. This is more robust than simply tracking the characteristics of the fourth highest 8-h day each year. (page 32)

17. At the individual monitors examined in detail, the background ozone levels on high 8-h ozone days has been steady over the past 11 years at around 0.065 ppmv. Over a shorter (7-year) period of record, the background ozone high 8-h days has been declining. (page 38)

18. The contribution of transient high ozone events to ozone levels on high 8-h ozone days has been relatively minor since 2002. (page 35)

19. The decline in importance of transient high ozone events may simply be a consequence of transient high ozone events preferentially occurring on low ozone days. (page 43)

20. At the examined stations, background ozone comprises 60% to 75% (on average) of the total ozone measured on high 8-h ozone days. This percentage was lower in the past. (page 32-38)

21. The average of the third to sixth highest annual background ozone levels (a measure of the design value in the absence of Houston emissions) has been falling steadily since the late 1990s and now stands at 0.062 ppmv. (page 41)

22. Days that violate the 8-h standard are more frequent than days that violate the 1-h standard. (page 44)

23. It is not clear from the statistical data whether emissions controls that bring Houston into compliance with the 1-h ozone standard would also bring it into compliance with the 8-h ozone standard. (page 44)

From Chapter 5:

24. Background ozone in Houston is most strongly correlated with meteorological parameters relating to a component of wind from the north on the day of the ozone and on each of the previous two days. (page 47)

25. Weaker winds also favor higher levels of background ozone. (page 47)

26. The local contribution to ozone is most strongly correlated with temperature (a positive correlation), with wind speed and the occurrence of precipitation both strongly negatively correlated. (page 47)

27. Temperature is not significantly correlated with background ozone levels. (page 47)

28. The difference in meteorological parameters related to background ozone and local contributions supports the approach of attempting to understand background ozone and local contributions separately. (page 47)

29. When the effects of wind speed and direction are excluded, precipitation appears to be an important suppressor of background ozone levels. (page 48)

30. When meteorological variables are controlled for by stepwise regression, there is significantly less local contribution on Sunday than on other days. (page 50)

From Chapter 6:

31. Regional-scale wind patterns are dominated by the *sea breeze rotation*, in which winds trace a circle or ellipse over the course of a 24-hour period. (page 52)

32. This rotation is not as apparent in surface observations over land, because nighttime winds tend to become calm in the lowest few tens of meters. (page 55)

33. The wind rotation leads to recirculation when large-scale mean resultant winds are smaller in magnitude than the amplitude of the sea breeze rotation, which is about 3 m/s (6 mph). (page 57)

34. The timing of recirculation is determined by the direction of the large-scale wind. (page 57)

35. The wind rotation leads to stagnation when large-scale mean resultant winds are only slightly weaker than the sea breeze rotation. (page 58)

36. Average 1-h maximum ozone levels are 0.090 to 0.110 when the 24-hour mean resultant wind at a nearby offshore buoy is less than 4 m/s (8 mph). (page 60)

37. Background ozone levels are highest (nearly 0.050 ppmv) when the 24-hour mean resultant wind is less than 1 m/s. (page 61)

38. The local contribution to 1-h ozone is nearly independent of wind speed below 4 m/s and decreases steadily at higher wind speeds, consistent with the sea breeze rotation model. (page 60)

39. The background contribution to 8-h ozone levels is larger than the local contribution at all wind speeds. (page 61)

40. The 8-h local contribution is highest (0.035 ppmv) at the lowest wind speeds and is in general less dependent on wind speeds than the 1-h local contribution. (page 61)

41. The north-south component of wind is a better indicator of background ozone levels than is wind speed itself. (page 62)

42. The highest average background ozone levels (0.046 ppmv) occur with a weak wind component from the north, while the lowest background ozone levels (less than 0.020 ppmv) occur with a strong wind component from the south. These wind variations are a reflection of the importance of the large-scale wind patterns in controlling background ozone. (page 62)

43. Background ozone and local contributions are quite variable and cannot be predicted accurately from wind indicators alone. (page 63-64)

44. The highest 1-h local contributions occur at 24-hour resultant wind speeds of 1.5 m/s to 4.5 m/s (3 mph to 8 mph). (page 63)

45. The highest 8-h local contributions occur at 24-hour resultant wind speeds of less than 1.5 m/s. (page 64)

46. Background ozone levels of 0.040 ppmv or greater, which increase the likelihood of an 8-h ozone exceedance, can be reached at almost any wind speed. (page 65)

47. Extremely high background ozone levels (greater than 0.105 ppmv) have occurred when the 24-hour resultant wind is nearly zero. (page 66)

48. High 1-h (and 8-h) local contributions are favored when the wind is light from the southeast, south, or southwest, but not when the wind is light from the north. The southerly winds are associated with daytime stagnation, while the northerly winds are associated with nighttime stagnation. Developing winds would likely carry any pollution blob resulting from nighttime stagnation eastward and southeastward over unmonitored areas. (page 66-69)

49. In all the major local contribution cases, it appears that the meteorological pattern and sea breeze rotation combine to produce local stagnation in the Houston area sometime between 7 AM and 4 PM. (page 69)

50. Background ozone is less strongly dependent on the background wind speed and direction. (page 70)

51. There is a strong tendency for high background ozone with winds from the northeast. (page 70)

52. The largest cluster of extreme background ozone events is found when the 24-hour resultant mean winds are 0.5 m/s (1 mph) or less. Under such conditions, the ozone plume from Houston on a given day would follow a circular path and end up back in Houston on the following day. At no time during this evolution would the actual winds be stagnant. (page 70)

53. Very high background ozone occurrences with winds from the west-southwest are associated with reversals in the 24-hour mean wind from the previous day and probably include the return of the previous day's pollution. (page 71-72)

54. Local contributions to 8-h ozone can be substantial even without pure stagnation, because an elongated but fairly concentrated plume can be as effective as a blob of high ozone in elevating 8-h levels at a fixed monitor. (page 73)

55. In general, the conditions favoring high ozone are similar for 1-h and 8-h exceedances, except that 8-h exceedances are more sensitive to background ozone levels and less sensitive to local contributions. (page 73)

56. Individual days will depart from the idealized wind patterns, but those patterns seem adequate for explaining the general conditions associated with most high ozone events in Houston. (page 73)

From Chapter 7:

57. Demonstration modeling in support of the 8-h standard should consider a broader range of meteorological conditions than 1-h modeling. (page 75)

58. Demonstration modeling should include an episode (or separate episodes) with both high background days and low background days. (page 75)

59. Days in which ozone from the previous day returns to Houston tend to be rare but extreme 8-h ozone events. They are likely to be difficult to model successfully because of the needed wind accuracy. (page 75)

60. Days with high pollution at inland stations are likely to involve different mixes of precursor emissions and different chemical processes than days with high pollution at coastal stations, and both types of events should be modeled. (page 76)

61. Emissions mixtures and photochemistry are unlikely to be substantially different for exceedances at different inland stations, given similar background ozone levels, so that variability need not be considered in episode selection. (page 76)

62. Monitor behavior suggests that the background trace species mixture may be fundamentally different during the spring background ozone peak than during the late summer background ozone peak. Exceedances are common in both seasons. Therefore, events in both seasons should be simulated. (page 76)

63. Modeling should focus not on the most extreme events, but rather events that fall within the third to sixth highest 8-h ozone levels in a given year. (page 77)

64. Several recent ozone episodes are suggested for modeling, including August 3-11, 2004 and May 23-31, 2003. (page 77-78)

65. Accurate simulations of 8-h ozone concentrations are likely to be less sensitive to accurate simulation of wind speed and direction than simulations of 1-h ozone concentrations, because 8-h exceedances are not as sensitive to stagnation. Other factors, such as mixing height, will be proportionally more important for accurate simulations. (page 78)

List of Figures

reconstructed by drawing or imagining a vector starting at the origin and ending at the ozone level dot. Cat 0: no exceedances. Cat 1: 1-h ozone between 0.125 ppmv and 0.155 ppmv. Cat 2: 1-h ozone between 0.155 ppmv and 0.190 ppmv. Cat 3: 1-h ozone greater than 0.190 ppmv. Cat 4: 1-h ozone less than 0.125 ppmv but 8-h ozone greater than 0.085 ppmv. (page 67)

Figure 26: Ozone 1-h local contributions as a function of 24-h mean resultant buoy wind, May-Sept, 1998-2003. Cat 0: local contribution less than 0.080 ppmv. Cat 1: local contribution between 0.080 and 0.100 ppmv. Cat 2: local contribution between 0.100 and 0.130 ppmv. Cat 3: local contribution greater than 0.130 ppmv. (page 68)

Figure 27: Background ozone concentrations as a function of 24-hour mean resultant buoy winds, May-Sept., 1998-2003. Cat 0: Background ozone less than 0.060 ppmv. Cat 1: Background ozone between 0.060 ppmv and 0.070 ppmv. Cat 2: Background ozone between 0.070 ppmv and 0.080 ppmv. Cat 3: Background ozone greater than 0.080 ppmv. (page 71)

Figure 28: Ozone 8-h local contributions as a function of 24-h mean resultant buoy wind, May-Sept, 1998-2003. Cat 0: local contribution less than 0.045 ppmv. Cat 1: local contribution between 0.045 and 0.060 ppmv. Cat 2: local contribution between 0.060 and 0.075 ppmv. Cat 3: local contribution greater than 0.075 ppmv. (page 72)

1. Introduction

Ozone concentrations in the Houston/Galveston metropolitan area (hereafter "Houston") are known to be sensitive to meteorological conditions. Current subjective ozone forecasting techniques rely on a small number of critical factors, most of which are meteorological in nature. High ozone is formed when winds are light, when planetary boundary layer (PBL) depths are low, when cloud cover is minimized, when background (preexisting) ozone levels are high, and when widespread convection does not occur until late in the day, if at all.

Conceptually, these factors play various roles in ozone formation. Widespread convection is a binary predictor: if it occurs, high levels of ozone are essentially prevented. Background ozone and cloud cover, on the other hand, are linear predictors. Decreased clouds or increased background ozone both lead to higher peak ozone values, but their effect is limited: small changes in cloud cover or background ozone can only produce proportionally small changes in peak ozone values. Finally, wind speed and PBL depth would be expected to be inversely proportional to peak ozone concentrations. When wind speed or PBL depth are small, peak ozone concentrations would be large and quite sensitive to specific wind speeds or PBL depths.

Previous studies of the meteorology of ozone events in Houston have typically focused on the role of surface wind patterns on high ozone events, both because of the important role of wind and because of the ready availability of surface wind data. Studies of the meteorological situations associated with one-hour ozone exceedances have found that very high ozone is typically associated with "wind reversals", a wind pattern that causes air parcels to stagnate and to pass over major emission sources twice within a 4-12 hour period. The wind reversals have been attributed to the land-sea breeze cycle. The most common reversal is from a northwesterly, offshore flow to a southeasterly, onshore flow. During certain events, high levels of ozone are especially likely when air stagnates over Galveston Bay, where vertical mixing is inhibited, during flow reversal prior to moving back onshore.

On many days with high one-hour ozone averages , monitors record a rapid rise and fall of ozone concentrations. These transient events, which have been given a variety of acronyms such as THOEs (for Transient High Ozone Events), have been variously attributed to meteorological conditions leading to transient stagnation and brief but massive upset emissions. These events, combined (or intertwined) with the unusual mix of photochemical pollutants emitted in the Houston Ship Channel area, have made Houston an unusual ozone city.

By Federal law and EPA regulation, the one-hour (1-h) standard holds that ozone levels, averaged over an hour, are not to exceed 0.12 ppmv. Rare exceptions to this limit are allowed, with the constraint that the limit is not to be exceeded more than three times in any three-year period at any particular monitoring site. Thus, the concept of 'design value' (fourth highest one-hour average in a three-year period) is computed and applied at individual stations within a metropolitan area.

The newer eight-hour (8-h) ozone standard holds that ozone levels, averaged over eight hours, are not to exceed 0.08 ppmv. Rare exceptions to this limit are allowed, with the constraint that, excluding the three highest events each year at each monitor, the three-year average of the (fourth) highest event at any station within the metropolitan area does not exceed the limit.

The purpose of this study is to develop a conceptual model of 8-h ozone exceedances in Houston. Part I (Nielsen-Gammon et al. 2005) examined the factors that control the background levels of ozone in eastern Texas. The key results from Part I, as they apply to Houston ozone, will be summarized in Chapter 2. This summary will be followed by examinations of: (Chapter 3) the annual cycle and geographical variation of ozone and ozone exceedances in Houston; (Chapter 4) the interannual trends of ozone exceedances in Houston; (Chapter 5) the statistical relationship between meteorological factors and high background levels and local concentrations of ozone; (Chapter 6) the relationship between background wind, local hourly winds, and high levels of ozone; and (Chapter 7) recommendations for episode selection and modeling for compliance with the 8-h standard. For convenience, a list of findings and recommendations is included as an executive summary.

To facilitate readability among persons without an extensive technical background, familiar units (such as Fahrenheit and miles per hour) will be used instead of MKS units (Celsius and meters per second). Time will generally be reported as Local (Central) Standard Time. Noon LST equals 11:00 LDT, which equals 18:00 UTC.

2. Local and Background Ozone in Houston

The ozone levels in a particular metropolitan area on a given day can be considered to consist of the ozone that would have existed in the absence of the metropolitan area (the "background" ozone) plus an additional amount that is due to local emissions sources (the "local contribution"). Because ozone formation is nonlinear, the local contribution is not independent of the background ozone but instead depends on the interaction between local emissions and constituents already present in the air. Background ozone is important because it represents that portion of a given day's ozone level that cannot be reduced by local emission controls.

For the purposes of this study, hourly ozone data was retrieved from the EPA data base for the Houston region for the period 1994-2003. Additional 2004 ozone data was obtained from the TCEQ web site. The EPA station identifiers differ from the common local identifiers, so a list of stations, numbers, and names is given in Table 1. Only the stations listed, which include at least three years of record extending at least through 2000, are included in this study. Stations which moved during the period of study are regarded as a single station for the purposes of this study.

Part I defined the daily 8-h background ozone for Houston as the smallest eight-hour average maximum ozone among a set of representative stations surrounding the Houston area. The stations used in the background ozone estimation are indicated in Table 1. Only stations on the perimeter of Houston were selected, because interior stations, even if they report lower ozone, are likely to have been affected by local emissions. Local NOx sources, for example, can potentially reduce ozone levels below the background.

Table 1: Houston ozone monitors used in this study.

EPA No.	CAMS No.	Station Name	Period of Data	Used for Background?
039-1003	C11	Clute	1994-6/2003	through 10/96
039-1016	C1016	Lake Jackson	6/2003-present	
039-1004	C84	Manvel Croix	9/2001-present	
167-0014	C34	Galveston	11/1996-present	yes
167-1002	C10	Texas City	1994-7/2004	
201-0024	C8	Aldine	1994-present	
201-0026	C15	Channelview	8/2001-present	
201-0029	C26	NW Harris	1994-present	yes
201-0046	C405	N Wayside	1994-present	
201-0047	C408	Lang	1994-present	
201-0051	C409	Croquet	1994-present	yes
201-0055	C53	Bayland Park	3/1998-present	
201-0062	C406	Monroe	1994-present	
201-0066	C410	Westhollow	7/1994-present	yes
201-0070	C81	HRO	5/2000-present	
201-1034	C1	Houston East	11/1995-present	
201-1035	C403	Clinton	1994-present	
201-1037	C407	Crawford	1994-3/2001	
201-0075	C411	Texas Ave	4/2001-present	
201-1039	C35	Deer Park	1/1997-present	
201-1050	C45	Seabrook	8/2001-present	
339-0089	C65	Conroe	10/1999-9/2001	yes
339-0078	C78	Conroe Reloc.	11/2001-present	yes

Two perimeter stations, C10 (Texas City) and C11 (Clute), would have been included in the background computations except that ozone levels tended to be markedly lower at C10 and C11 than at C34 (Galveston) under southeast and east wind conditions, despite the fact that C34 has no significant upwind sources. On occasion, C10 or C11 would have the lowest ozone levels even when the wind was blowing from Houston toward the monitors. Therefore, C10 and C11 were regarded as suspicious for background ozone estimation and were not used, except that data from C11 were used for the early part of the period, prior to the installation of C34.

Further information regarding the selection of stations for measuring background ozone in Houston may be found in Part I.

Beyond this screening of stations, no attempt was made to assign background ozone levels based on wind direction. Nevertheless, it was confirmed in Part I that the station reporting the lowest 8-h maximum ozone were typically upwind of Houston.

The 1998-2003 ozone climatology for non-precipitation days (i.e., days without rainfall) is shown in Fig. 1. The annual cycle of ozone has a maximum in early September of 0.089 ppmv, and a minimum in late December of 0.038 ppmv. Prominent also is a secondary peak of 0.073 ppmv in early May and a midsummer minimum of 0.062 ppmv in early July. This pattern is the combination of the annual cycle of background ozone, which reaches maxima in the spring and late summer/early fall and minima in early winter and early summer, and the annual cycle of the local contribution to ozone, which reaches a maximum in summer and a minimum in winter.

According to the analysis of Part I, the July minimum and September peak of background ozone are caused by changing frequencies of large-scale wind patterns which advect relatively clean air from the south in July and relatively polluted air from the northeast in September. The secondary maximum of background ozone in spring is weakly associated with an increase in favorable transport winds, but is primarily due to a

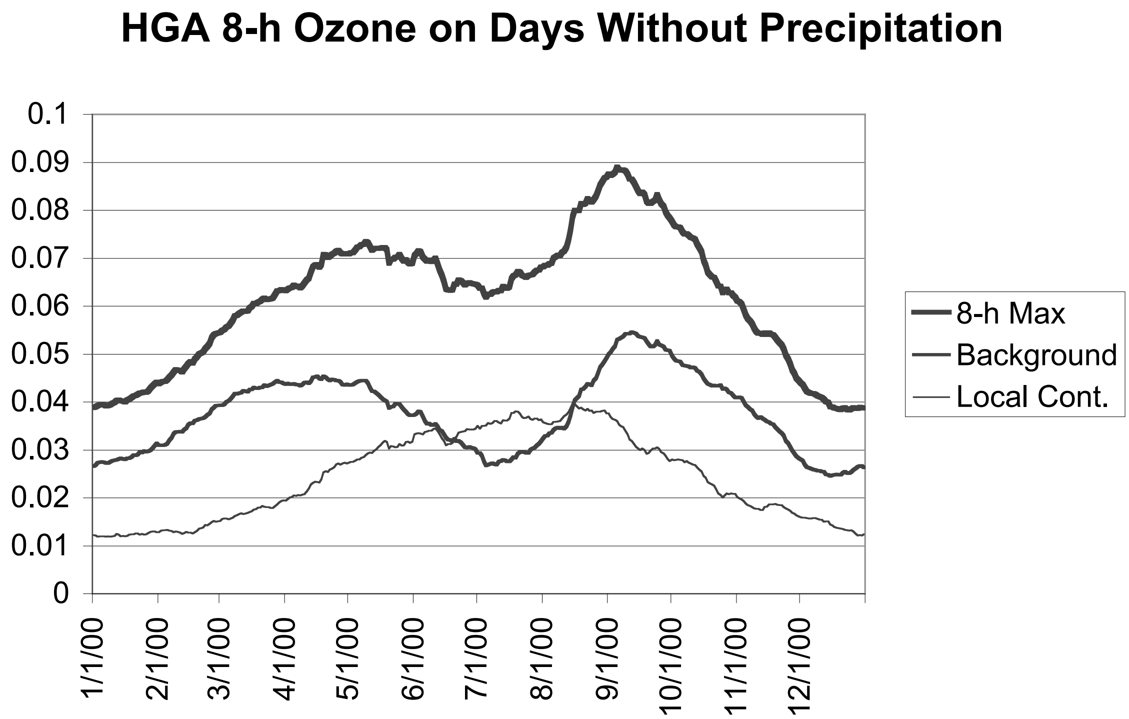

Figure 1: 31-day running mean of daily average background, local contribution, and maximum 8-h ozone in the Houston region, 1998-2003.

much larger-scale springtime peak in ambient ozone that is also found in the western United States and southeastern United States. The leading explanations for this peak involve the longer lifetime of tropospheric ozone in spring and the buildup of ozone precursors in winter. The July minimum is most pronounced in south Texas and weakest in north Texas.

The meteorological conditions that are responsible for the late summer peak in the local contribution will be discussed in Chapter 5. Suffice it to say at this point that the annual cycle in local contribution is not much different from what would be expected from the annual cycle of solar radiation (maximum in late June) and daytime temperatures (maximum in late July and early August). The radiation and temperature modulate the photochemistry from emissions which themselves are nearly constant.

The partitioning between background and local contributions of ozone is unusual in Houston in that during part of the year the peak ozone is dominated by local sources. All other areas of central and eastern Texas are dominated by background ozone throughout the year. The difference is caused primarily by an enhanced local contribution in Houston, although background ozone levels are also somewhat lower than those farther north.

For more details regarding the information in this chapter, see Part I (Nielsen-Gammon et al. 2005).

3. The Climatology and Geography of 8-h Ozone Exceedances in Houston

The frequency of 8-h ozone exceedances in Houston (Fig. 2) show an annual cycle that is similar to the annual cycle of average ozone concentrations. Over the past seven years, ozone exceedances have been most frequent in August and September, with an average of 10-12 ozone exceedances per month. A relative minimum in the number of violations occurs in July on average, although some years (2000, 2004) have several July exceedances. In the spring, the number of exceedances mimics the secondary maximum

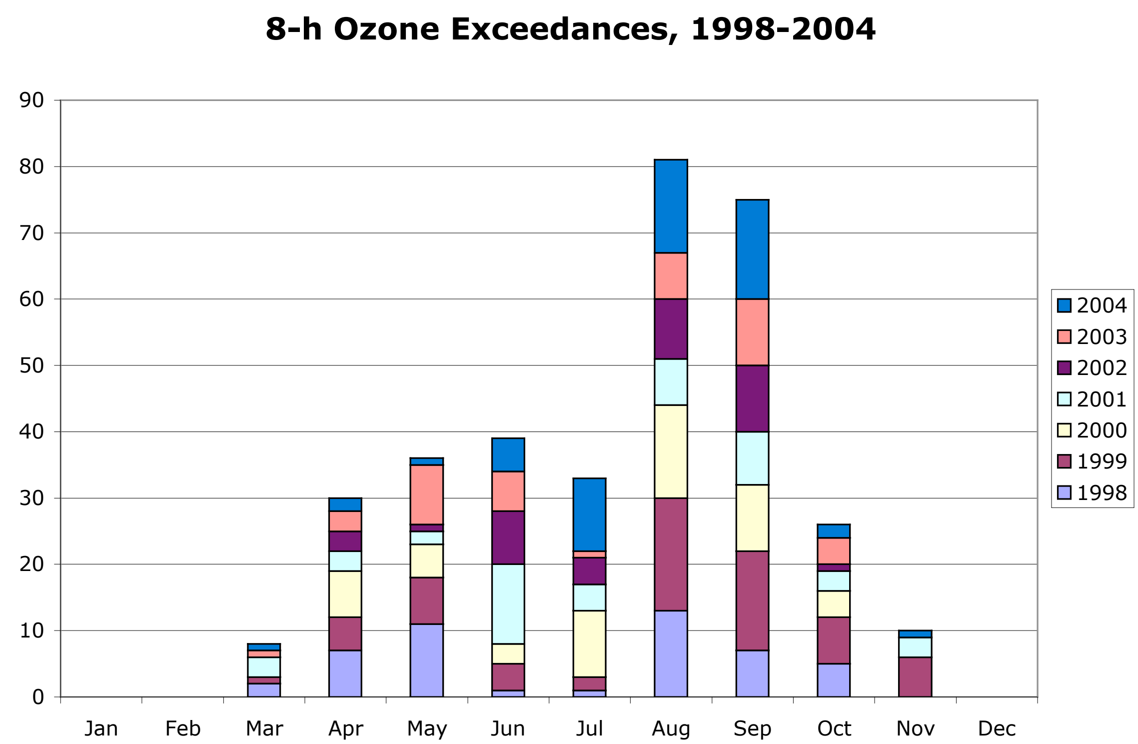

Figure 2: Days in which the 8-h standard was violated at one or more monitor, by month. The 1998-2003 count uses all stations in the EPA database, while the 2004 count uses all stations in the TCEQ database. The 2004 data is through November.

in average 8-h maximum ozone (compare with Fig. 1). As with July, the number of exceedances in particular months varies substantially from year to year. The average annual number of exceedances in March through July (21) almost equals the average annual number of exceedances in August and September (22). No exceedances were recorded in the months of December, January, and February.

Figure 3 is a plot of the spatial distribution of the frequency of 8-h ozone exceedances during 1998-2003. The stations are plotted in their approximate relative locations, with C411 being in downtown Houston. The size of each pie chart corresponds to the total

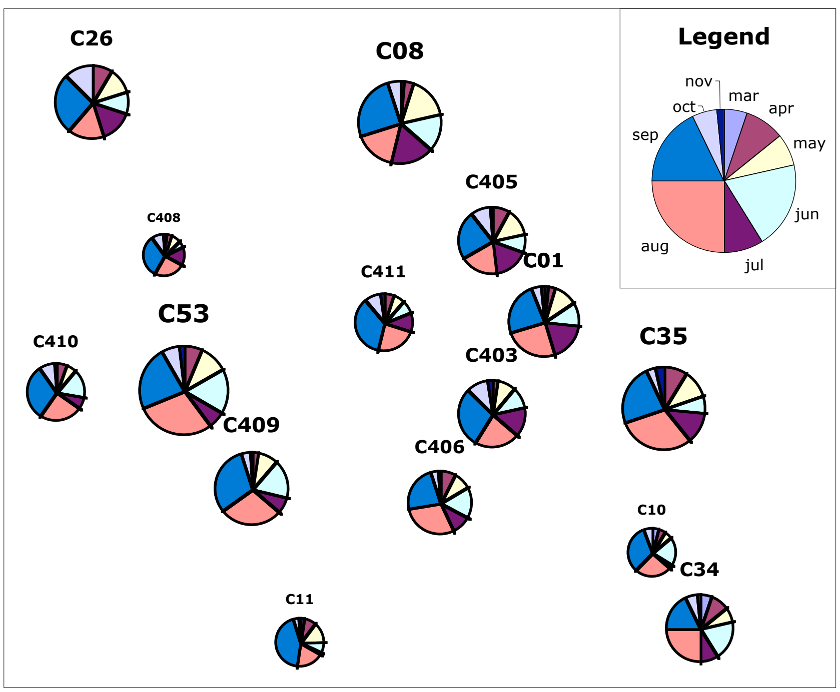

Figure 3: Ozone exceedances and months of high ozone. Stations are plotted in their relative geographical locations (not to scale), with downtown Houston in the center. The size of each station's pie chart corresponds to the relative number of exceedances, while the pie chart itself indicates the months in which high ozone is observed.

number of exceedances at each station. The divisions within the pie chart indicate the relative frequency of high ozone days (defined as the eight highest 8-h ozone levels in each year) per month. Thus, Fig. 3 is useful for understanding the geographical distribution of ozone exceedances as well as any spatial differences in the seasonality of high ozone.

The stations with the largest number of ozone exceedances during 1998-2003 are also listed in Table 2. The largest number of exceedances per year is 18 at C53, with C8 a close second. Fig. 3 shows that these two sites are west and north of downtown Houston, respectively, and they are both far from the major cluster of point sources in the Ship Channel area.

Table 2: Average number of 8-h ozone exceedances, 1998-2003.

Station	Exceedances	Station	Exceedances
C53: Bayland Park	18	C403: Clinton	10
C8: Aldine	17	C406: Monroe	9
C35: Deer Park	15	C410: Westhollow	8
C409: Croquet	14	C411: Texas Ave	7
C26: NW Harris	14	C10: Texas City	6
C1: Houston East	11	C1016: Lake Jackson	5
C405: N Wayside	11	C408: Lang	4
C34: Galveston	10		

Later it will be shown that winds on high ozone days at C53 tend to be from the east while winds at high ozone days at C8 tend to be from the southeast. It will also be shown that light winds from the east-southeast are common as well, so one would expect stations located between C53 and C8 to have similarly high numbers of ozone exceedances. However, Fig. 3 and Table 2 show that this is not the case. C408 had the smallest number of exceedances of any station in the Houston area, and C411 also experienced a relatively small number of exceedances. In general, there is no tendency for stations with high (or low) numbers of exceedances to be located adjacent to stations with similarly high (or low) numbers of exceedances.

There is no meteorological explanation for this high degree of spatial variability of ozone exceedances. Other potential explanations include (1) poor calibration of individual monitors; (2) poor performance of individual monitors; (3) local variations in NOx sources, producing ozone scavenging; and (4) local variations in dry deposition of ozone due to surface roughness and obstructions.

While it is not possible to determine from the ozone exceedance data which, if any, of these four explanations are correct, there is some additional relevant information. First, the relatively low frequency of ozone exceedances is mirrored by a relatively high frequency of very low ozone days. As mentioned earlier, C10 and C11/1016 tended to have lower ozone than C34 even when winds were from the south or southeast. Station C408, which was also a candidate perimeter site for estimating background ozone, typically had lower concentrations than C26 and C78 when the wind was from the north and the air at C26 and C78 should have been more pristine than the air at C408 under those conditions. Second, the two stations with the smallest frequency of high ozone occurrences during May and June are C408 and C407/411, suggesting that the processes that make ozone readings lower at C408 and C407/411 are particularly efficient in May and June.

All of the apparent explanations for the low ozone readings at selected stations are station or neighborhood-specific, so the low number of exceedances at those stations should not be regarded as representative of ozone levels in surrounding neighborhoods. It is also not possible to say which stations are affected by the low ozone problems, since no individual station is known to record the 'true' number of ozone exceedances. Therefore, given the ozone monitoring network in place during 1998-2003, *it is not possible to determine the true spatial distribution of the frequency of 8-h ozone levels greater than 0.084 ppmv within the Houston metropolitan area*. Among the aspects of the true ozone pattern that cannot be determined are the direction from downtown Houston (or from the Ship Channel) of the highest 8-h ozone values or the distance from Houston (or from the Ship Channel) of the highest 8-h ozone values.

To the extent that the spatial pattern of high ozone levels within Houston is of interest, efforts should be made to determine the cause of the monitor-to-monitor discrepancies. Depending on the cause, a program to cross-validate ozone monitors or determine the local representativeness of measured ozone levels may be appropriate.

Some spatial patterns are coherent in Fig. 3. For example, the stations with more than half of their high ozone days in August and September are exclusively those located at and south of the latitude of downtown Houston and the Ship Channel, suggesting a relatively high frequency of northeast winds during that period compared to the spring and early summer. The only southern station with fewer than half its high ozone days in

August and September is C34 (Galveston). Conversely, stations with a relatively large frequency of high ozone days in July are located at and north of the latitude of downtown Houston and the Ship Channel, suggesting that high ozone occurs primarily during southerly and southeasterly winds in that month. High ozone days are relatively more likely in March through June at C34.

4. Interannual Variations and Trends in Ozone Exceedances

Because of changes in the network configuration and database, total annual counts of exceedance events are not an accurate measure of interannual trends in ozone across a metropolitan area. For that sort of analysis, station-by-station trends are much more meaningful. For this purpose, 8-h ozone design values will be examined, since the design values are most relevant to future compliance with the 8-h standard. The design value is defined as the three-year average of the fourth-highest daily 8-h maximum ozone concentration observed at a particular station.

Figure 4 shows the 8-h design value trends at all stations in the Houston area. Even though the design values represent three-year averages, there is still considerable variability from year to year. Despite the variability, there is a clear downward trend in the design values at almost all stations in the Houston area. The sole exception is C11/C1016, which moved from Clute to Lake Jackson in June 2003. It is possible that the apparent lack of a downward trend at that pair of monitors is due to spatial differences in ozone levels at the two sites.

The overall design value for Houston during this period peaked at 0.118 ppmv in 1998 and has fallen every year since then. For the most recent three-year period, 2002-2004, the highest 8-h design value for Houston is 0.102 ppmv at C53 (Bayland Park), with C35 (Deer Park) (at 0.101 ppmv) a close second. One station, C408 (Lang), has a design value below the 0.084 allowed maximum.

While the overall downward trend likely reflects the impact of emission reductions, the year-to-year changes are attributable to meteorological variability. Similarly, year-to-

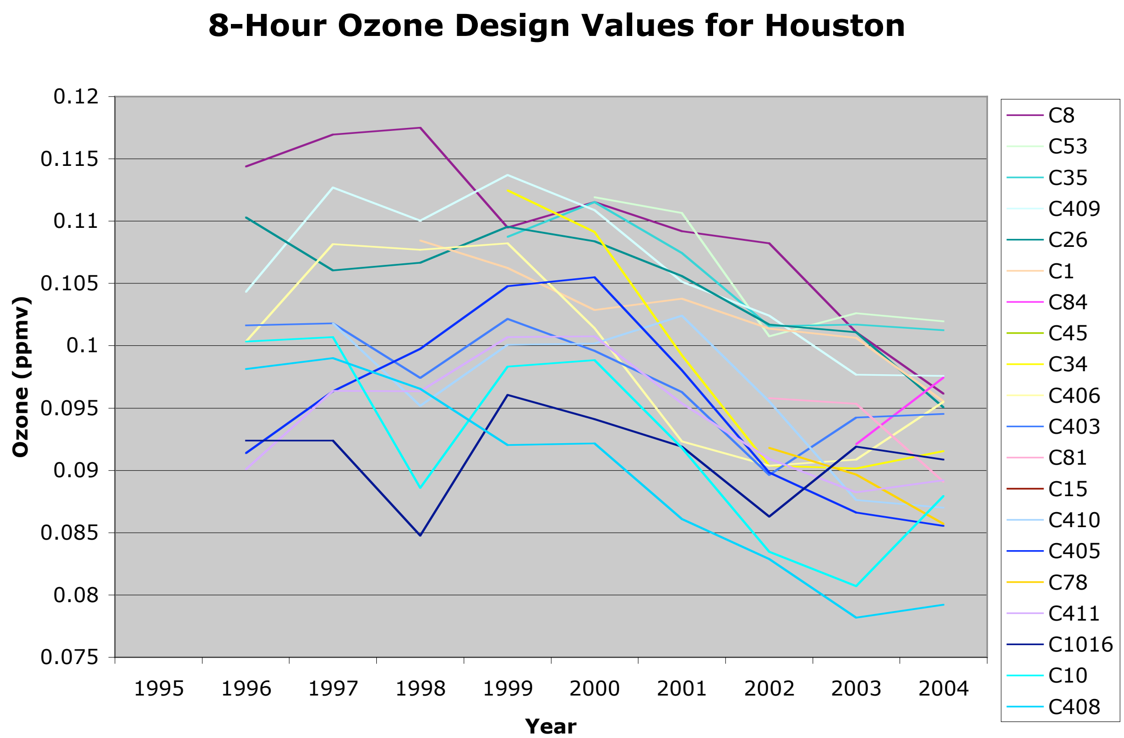

Figure 4: 8-h ozone design values for Houston monitors, computed as the three-year average (labeled with the ending years) of the fourth-highest annual ozone level at each monitor. The legend depicts the monitoring sites in approximate order of design value.

year differences in which stations have higher design values probably reflect differences in wind direction on the particular high ozone days in each three-year period.

To examine the year-to-year changes, five stations will be selected as benchmarks for the Houston area. These stations, C8 (Aldine), C26 (NW Harris), C34 (Galveston), C35 (Deer Park), and C53 (Bayland Park), are chosen because they are located in different areas of Houston and all have relatively high 8-h design values or exceedance frequencies. Since the greatest interest is in ozone events on design value days, one might simply examine the trends in the fourth-highest 8-h ozone level. However, to expand the sample size and reduce the effect of random variability, the charts presented below are based on the ozone events in each year ranking third through sixth highest. These will be referred to as 3-6 ozone levels in the following discussion. Also plotted for reference is the 8-h design value, which is the three-year running mean of the fourth-highest 8-h ozone level. It can be seen from the charts below that the 3-6 ozone levels closely track the design value.

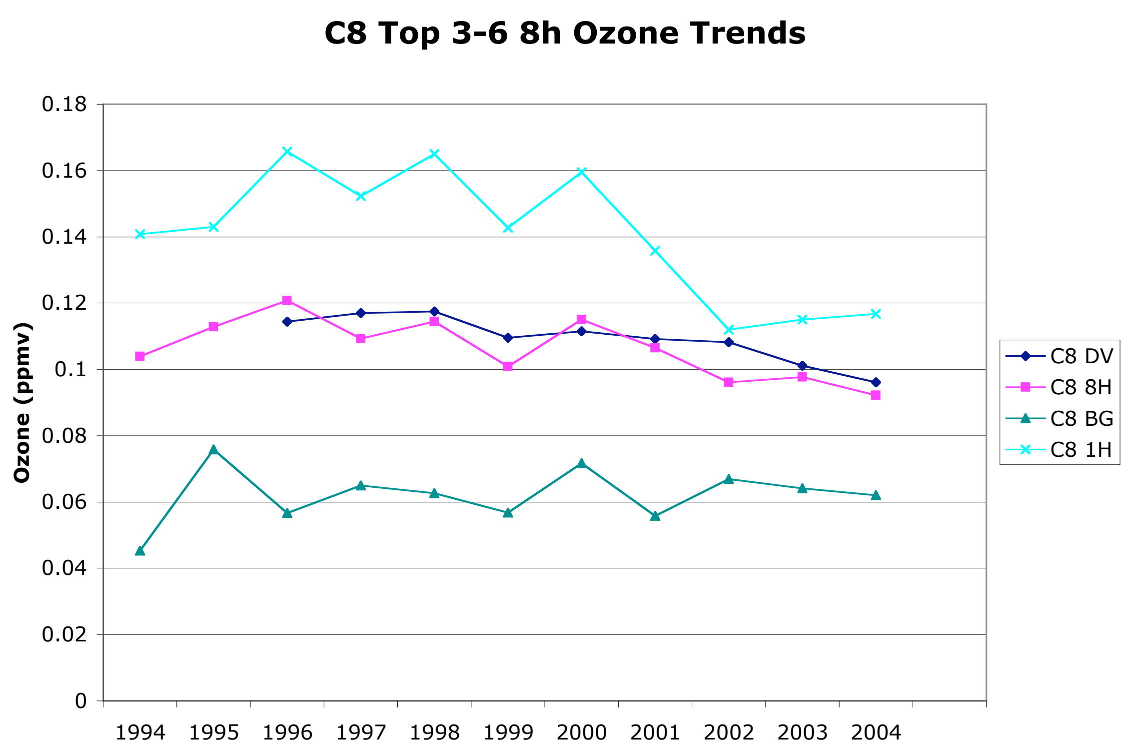

Figure 5: Trends in characteristics of the third- to sixth-highest 8-h ozone events at station C8 (Aldine). BG: Average background 8-h ozone levels during the third- to sixth-highest 8-h ozone events at C8. 8H: Average of the third- to sixth-highest 8-h ozone levels at C8. DV: 8-h design value at C8. 1H: Average 1-h ozone peak at C8 on days with the third- to sixth-highest 8-h ozone levels at C8.

At station C8 (Aldine) (Fig. 5), the 3-6 ozone levels have been declining in tandem with the design value since the late 1980s. The background ozone levels on 3-6 days has been fairly steady at 0.050 to 0.070 ppmv during that period. Thus, the proportion of the 3-6 ozone levels that consists of excess over background has decreased in absolute terms from around 0.050 ppmv to 0.030 ppmv, and in relative terms from about 45% to 30%-40%.

The average 1-h ozone maximum at C8 on the top 3-6 8-h days has also undergone a decline. In the late 1990s, days close to the design value for 8-h ozone had 1-h ozone peaks near 0.160 ppmv, while more recently those peaks have averaged 0.120 ppmv.

On days with very rapid rises, narrow peaks, and rapid falls of ozone, the difference between the 1-h and 8-h ozone maxima will necessarily be large. Conversely, days in which the ozone levels are fairly steady, with no significant pockets of extremely high ozone passing the sensor, will have 1-h maxima only slightly larger than 8-h maxima. Thus, the absolute difference between the 1-h and 8-h maxima is a direct indication of the extent to which transient high ozone events affect 8-h design value days.

In the case of C8, 1-h peaks were about 0.040 ppmv higher than 8-h peaks from 1996 through 2000. A dramatic change then occurred, such that the difference between 1-h and 8-h peaks has been about 0.020 since 2002. Thus, transient high ozone events are much less important for the 8-h standard at C8 now than they were in the late 1990s.

The record for C26 (NW Harris) (Fig. 6) is in many respects similar to that of C8 (Fig. 5). Both the 8-h design value and the top 3-6 8-h values are similar in magnitude to that at C8 and have been steadily declining. The 3-6 background ozone has been erratic

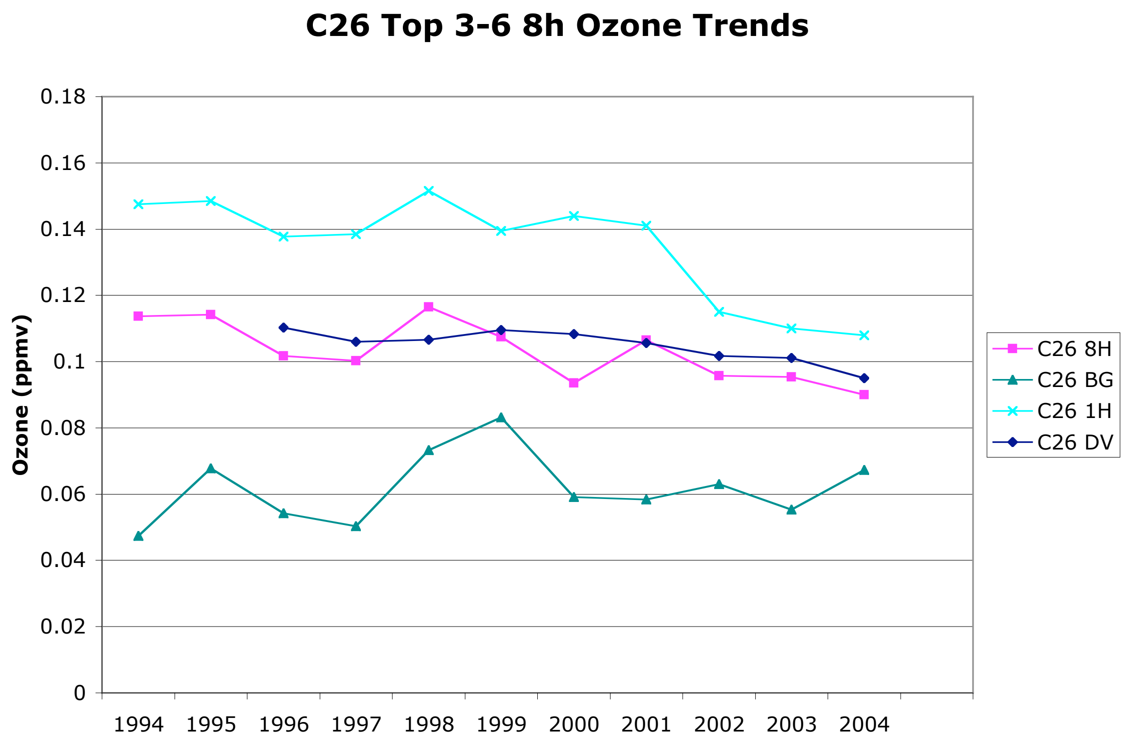

Figure 6: Trends in characteristics of the third- to sixth-highest 8-h ozone events at station C26 (NW Harris).

but without significant trend during the same period, leading to a reduction in the amount and proportion of local contributions to the 3-6 8-h ozone values. In general, background ozone levels at C26 are similar to those at C8, while 8-h ozone maxima and design values are 0.000 to 0.005 ppmv less. Thus, the proportion of ozone due to local contributions at C26 is a bit less than at C8, falling to 25% in 2004.

With local contributions less important at C26, one might also expect ozone levels to be steadier, so that the difference between 1-h and 8-h ozone levels should be smaller at C26 than at C8. This is indeed the case: the 1-h peaks on the 3-6 8-h days are about 0.010 ppmv lower at C26. The pattern, however, is very consistent across stations: a relatively large difference, indicating transient high ozone events, through 2001; a relatively small difference, indicating little impact from transient high ozone events, from 2002 through 2004. Included in the average 8-h to 1-h difference in 2000 is a 0.070 ppmv difference (1-h maximum of 0.157 ppmv, 8-h maximum of 0.087 ppmv) that took place on August 25, 2000, a classic transient high ozone event during the heavily-analyzed 1-h ozone episode.

It is important to realize that there is little overlap between the two sets of data: only three of the twelve days from 2002-2004 that were third through sixth highest in 8-h ozone at C8 were also third through sixth highest at C26. Therefore, it appears that the decline in importance of transient high ozone events is not confined to a particular station or a small number of events.

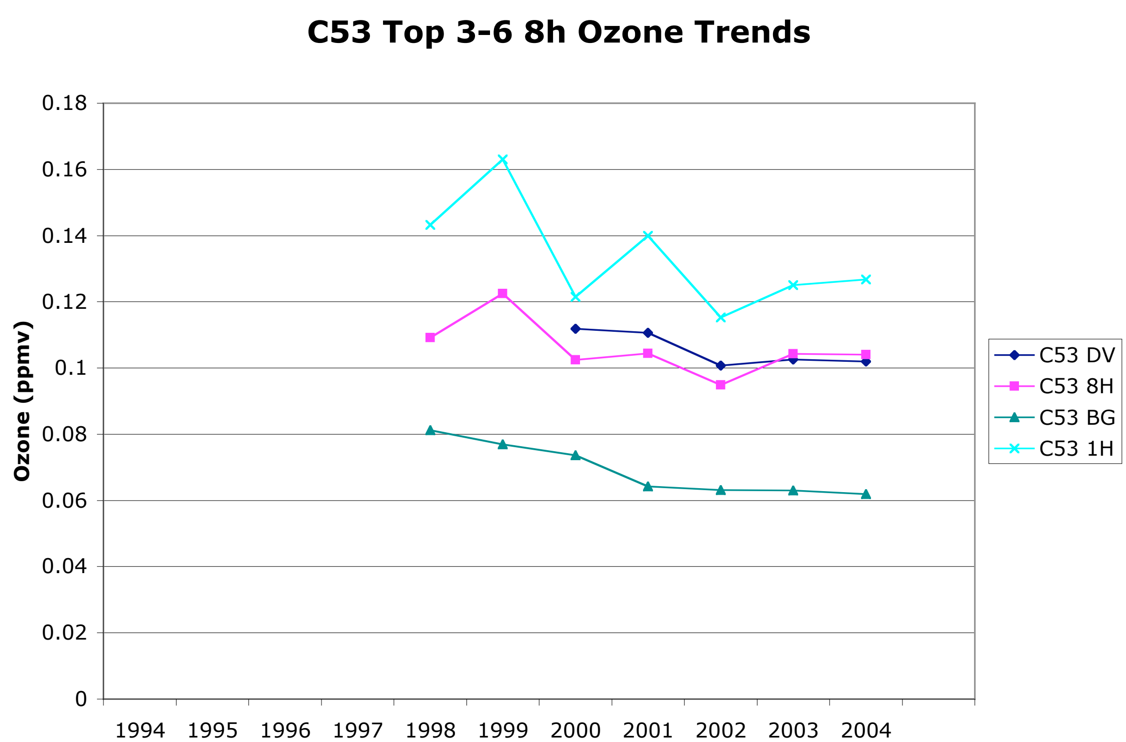

Figure 7: Trends in characteristics of the third- to sixth-highest 8-h ozone events at station C53 (Bayland Park).

At station C53 (Bayland Park) (Fig. 7), there are no major surprises other than the relatively small 1-h value in the year 2000. Background ozone levels during the top 3-6 events tend to be similar at C53 to the other two stations. The apparently steady decline in background ozone at C53 actually agrees very closely with trends and levels at C26 during the same period. With a somewhat larger local contribution, the 8-h design value is about 0.005 ppmv higher at C53.

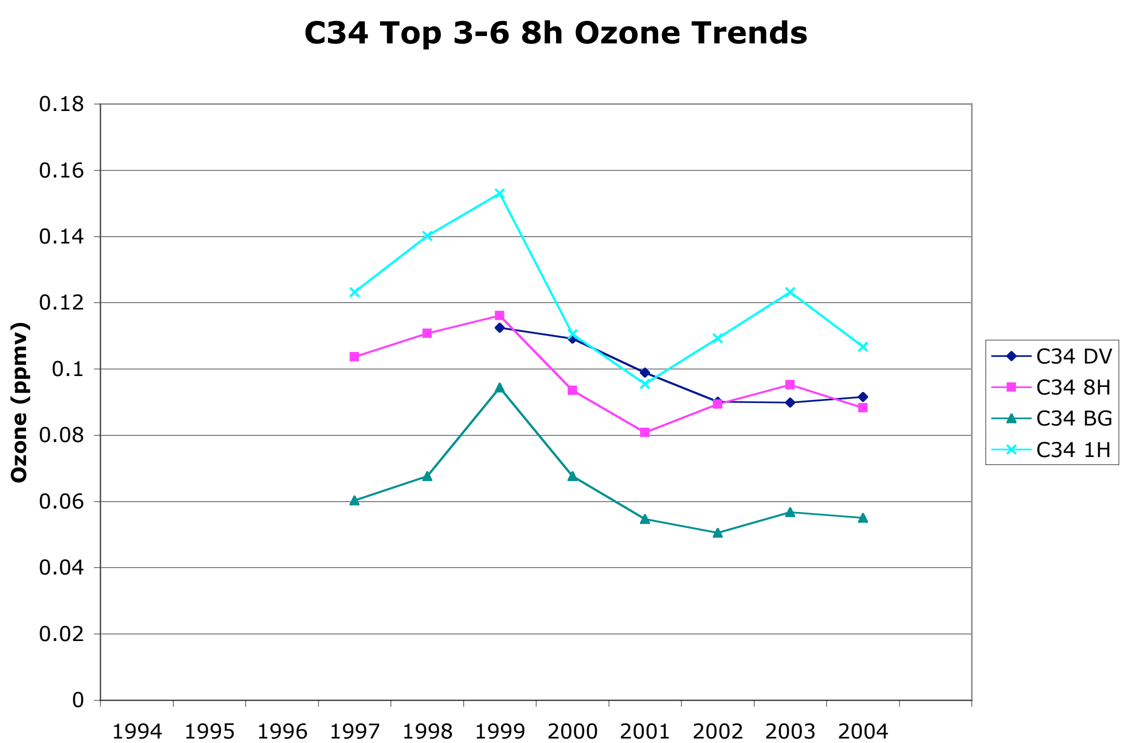

Figure 8: Trends in characteristics of the third- to sixth-highest 8-h ozone events at station C34 (Galveston).

Continuing in a counterclockwise manner around Houston, station C34 (Galveston) (Fig. 8) exhibits considerably more interannual variability than the other three stations.

There is a downward trend in all ozone levels, but this trend is comparable in magnitude to the year-to-year variations in ozone. The variability appears to be driven by background ozone levels, which have a wider range here than at the other stations. Since the background levels on any given day are by definition the same at C34 as at other stations, it must be the case that the urban ozone plume is a relatively rare occurrence at C34, such that there won't necessary be many times when the urban plume is felt at C34 on days with high background ozone.

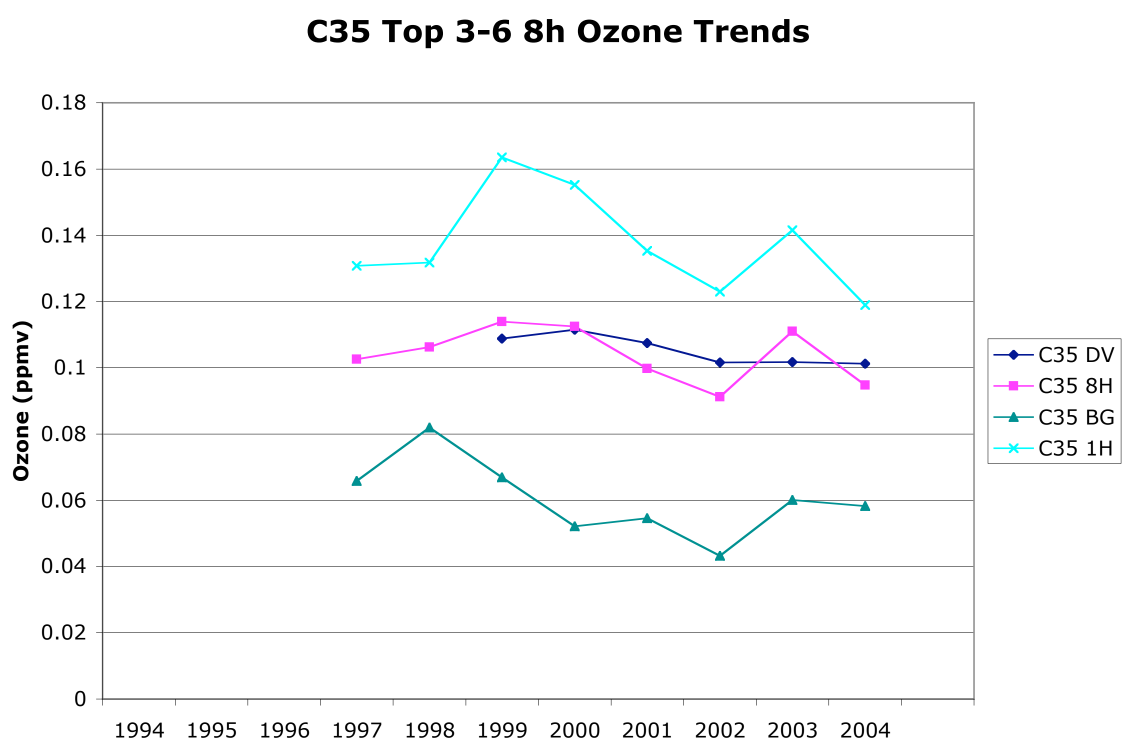

Figure 9: Trends in characteristics of the third- to sixth-highest 8-h ozone events at station C35 (Deer Park).

Station C35 (Deer Park) is in some aspects the opposite of station C34. Whereas C34 top 3-6 ozone levels were driven by background ozone, the top 3-6 at C35 are driven by local contributions, which are higher (0.030 to 0.060 ppmv) here than at the other four stations. As at the other stations, there is a downward trend in the 1-h ozone peaks, but the difference between 1-h and 8-h values remains somewhat larger than at other stations, suggesting that some transient high ozone events still occur at C35 on high 8-h ozone days. Trends are downward in both background ozone and total ozone, but unlike the other stations, the local contribution at C35 does not appear to have declined.

In summary, the individual station histories all show a decline in 8-h design values over the past decade. This decline is primarily associated with a decline in the local contribution to high ozone. The background ozone levels on top 3-6 days have remained steady over the past eleven years, leading to a much greater proportion of the high 8-h ozone values being attributable to background ozone. Over just the past seven years, background ozone levels have declined.

It is possible that a decline in local contribution can by itself mask a smaller decline in background ozone levels during extreme events. This effect can be illustrated by a scatterplot of the local contribution to C8 8-h ozone versus background concentrations (Fig. 10). The scatterplot shows that when the local contribution is small, the background levels tend to be small too, but there is little correlation between the two when ozone levels are high. The diagonal line represents the 8-h standard; exceedances are to the right of the line, where the sum of the background ozone and local contribution exceed 0.084 ppmv. Negative local contributions correspond to situations in which the 8-h maximum ozone at C8 is lower than at any of the more rural stations surrounding Houston and are presumably associated with scavenging within NOx-rich plumes.

If emissions controls are reducing the local contribution to ozone, they would be expected to do so in rough proportion to the magnitude of the local contribution on any

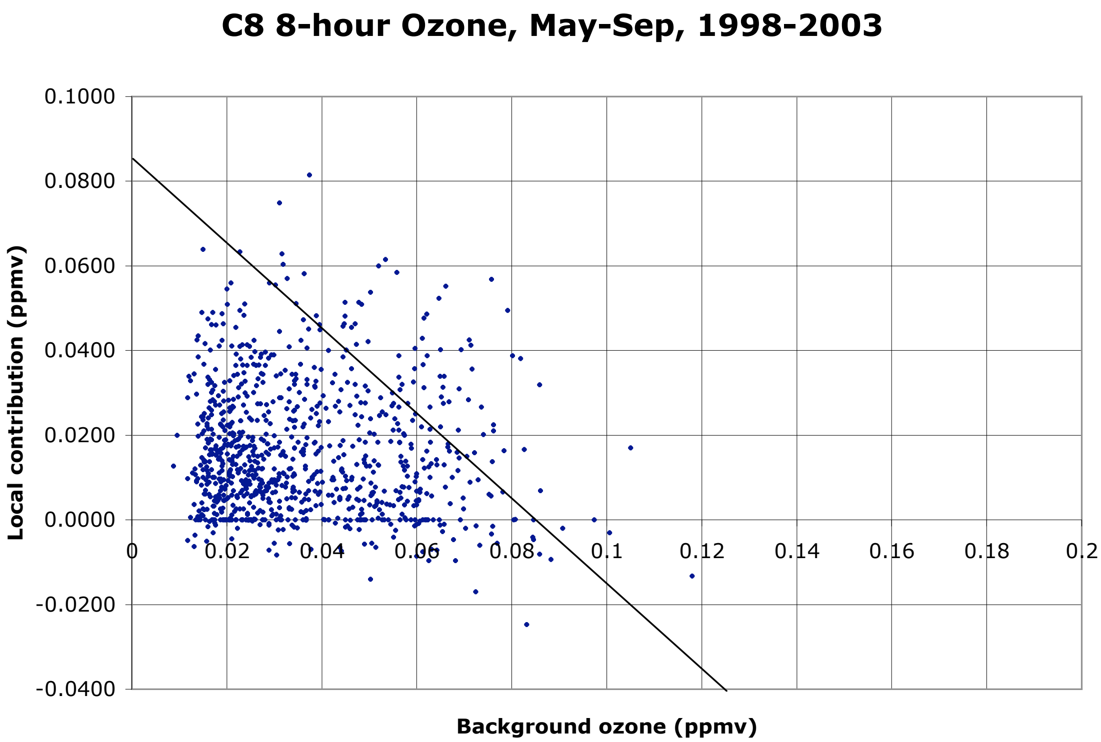

Figure 10: Background ozone levels versus the local contribution at C8 during the hot season. Points to the right of the diagonal line exceed the 8-h standard at C8. Points with an apparent local contribution of zero are actually days with C8 data missing.

given day. Considering points to the right of the exceedance line, those with high local contributions will move down on the diagram a great deal, while those with small local contributions will move hardly at all. Thus, considering exceedances, a greater proportion of exceedances will be those with high background ozone levels, and the average background ozone level on those exceedance days will also be higher.

The available evidence indicates that monitored background ozone levels may be systematically declining, albeit somewhat more slowly than the local contribution. Figure 11 shows the annual cycle of background ozone levels averaged over the periods 1994-2003, 1998-2003, and 2000-2003. The most recent averaging period has lower

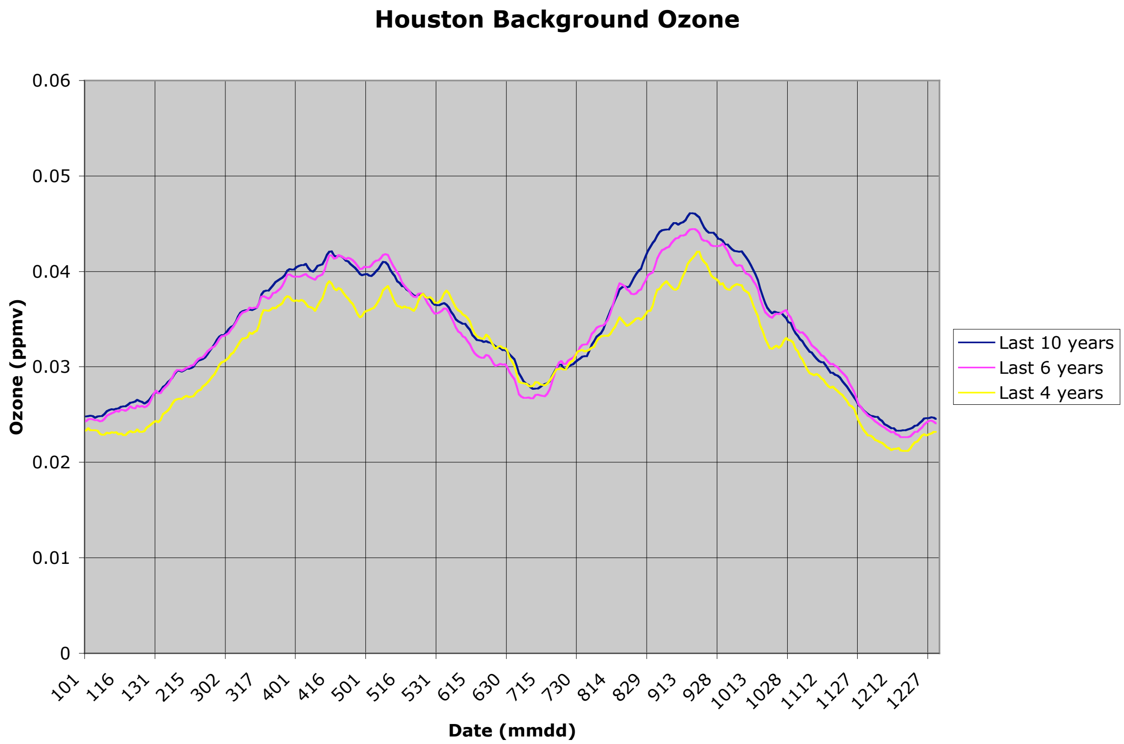

Figure 11: Background 8-h ozone in Houston, averaged over the 10-year period 1994-2003 (blue), the 6-year period 1998-2003 (purple), and the 4-year period 2000-2003 (yellow). A triangular filter was used to smooth the data.

background ozone levels except during June and July. The decline in background ozone levels is generally close to 0.003 ppmv. The decline may plausibly be attributed to a reduction in anthropogenic ozone from the continental United States, since the decline shows up in all months except those which are most dominated by southerly winds from the tropics.

One may also examine the trends in high levels of background ozone by tracking the third to sixth highest background ozone levels in a given year (Fig. 12). This statistic is less subject to individual, unique days than simply the highest or fourth highest background ozone level. The average of the third to sixth highest background ozone

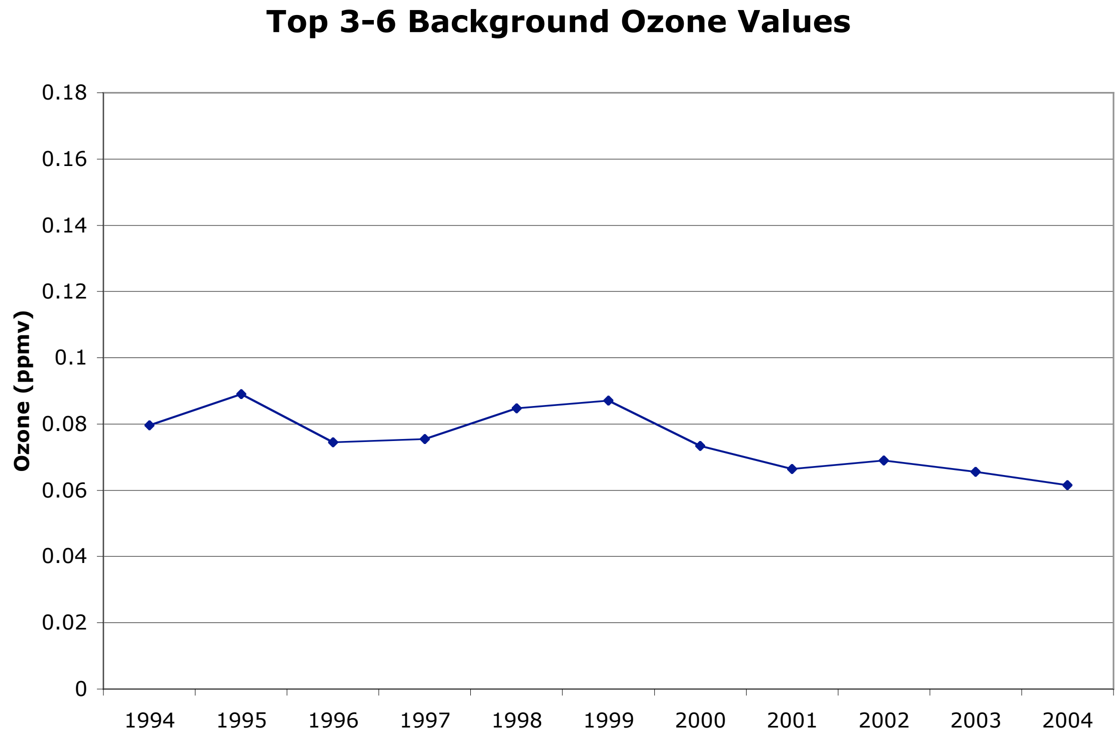

Figure 12: The average of the third through sixth highest background ozone levels in Houston, by year.

level is useful because it provides an estimate of how low the design value for 8-h ozone in Houston can become if all emissions were eliminated. This "background design value" overall shows a general downward trend and now sttands at 0.062 ppmv. The magnitude of this trend is greater than –0.001 ppmv per year, an amount consistent with the differences shown in Fig. 11.

Because the background ozone design value is 0.060 ppmv to 0.070 ppmv, it is not possible for the actual design values in Houston to drop below these levels without removal of background ozone, unless the downward trend in background ozone continues. Similarly, the background contribution to the 8-h design values will generally be capped at around 0.060 to 0.070 ppmv.

The individual station plots suggested that transient high ozone events are becoming less common. To check this possibility, Fig. 13 displays the maximum 8-h ozone in Houston as a function of the maximum 1-h ozone in Houston. The thick solid lines show the federal standards for 1-h and 8-h ozone. The leftmost diagonal line corresponds to points in which 1-h ozone equals 8-h ozone, that is, constant ozone levels for eight hours. Points to the left of this diagonal are impossible.

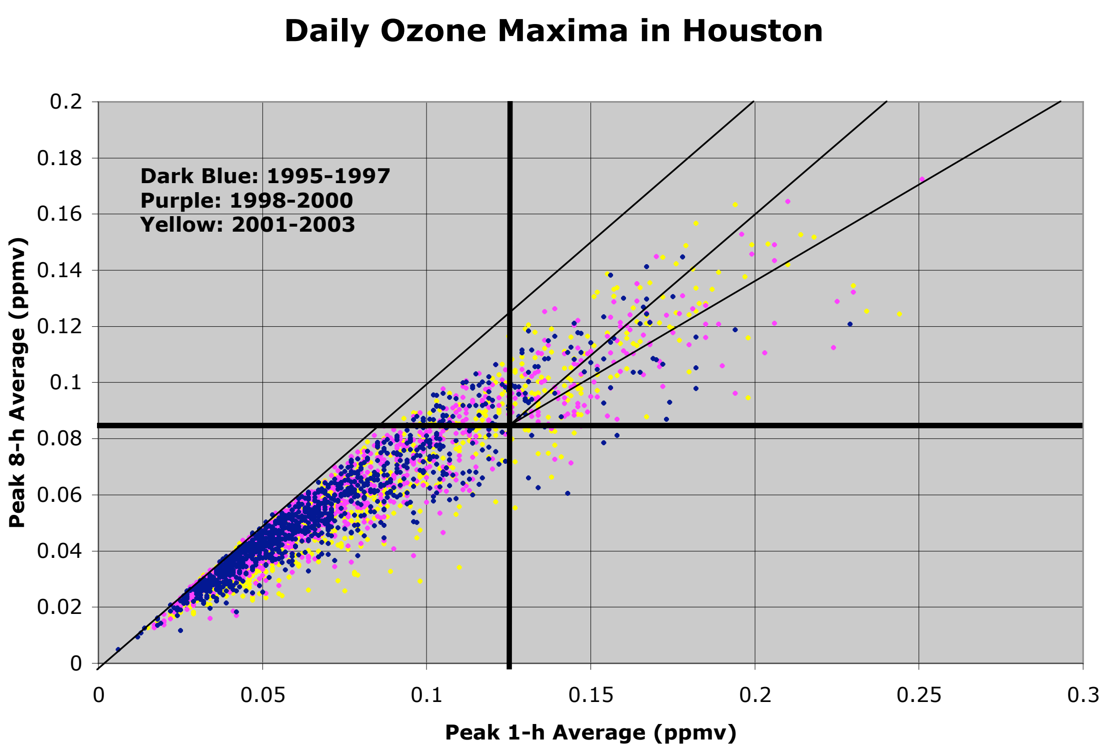

Figure 13: Daily peak ozone levels in Houston, 1-h maxima versus 8-h maxima. Colors represent different periods. See text for explanation of lines.

The dots are color-coded by year of occurrence. Focusing on points with very high ozone values and very large differences between 1-h peaks and 8-h peaks (i.e., those points above the thick horizontal line and farthest to the right of the leftmost diagonal), it is clear that the number of such occurrences is much smaller in the 2001-2003 time frame. At the same time, a relatively higher absolute number (and proportion) of high 1-h events in 2001-2003 lie close to the leftmost diagonal, meaning that transient high ozone events have become less common on high ozone days.

Inspection of Fig. 13 shows that there are still occasional transient high ozone events, except that those during the past three (now four) years have occurred predominantly when 8-h ozone levels (and presumably background levels as well) were low. When the peak 8-h ozone level is less than 0.085 ppmv and the peak 1-h ozone level is at least twice the 8-h ozone level, 19 of 34 events have occurred during the last three years of the nine-year period. It therefore seems possible that Houston has been lucky the past four years (and unlucky the previous six) in that transient high ozone events have recently taken place mainly when ozone levels were otherwise low. If so, the recent dearth of transient high ozone events on high ozone days would be unlikely to continue.

The middle diagonal line represents points which would exactly meet the 8-h standard if the ozone was reduced by a uniform amount so as to bring them into compliance with the 1-h standard. Points to the left of this diagonal line would still violate the 8-h standard even if they were brought into compliance with the 1-h standard by a fixed reduction in ozone.

The rightmost diagonal line is similar to the middle one, except that it corresponds to all points for which a fractional reduction in ozone levels would simultaneously bring the points into compliance with both the 1-h standard and the 8-h standard. Points to the left of this diagonal line would still violate the 8-h standard even if they were brought into compliance with the 1-h standard by a fractional reduction in ozone.

Considering points that violate both standards, targeted reductions in ozone to attain the 1-h standard would only allow about half or fewer of the points to also attain the 8-h standard. Furthermore, there are many points (those in the upper left quadrant) that violate the 8-h standard without violating the 1-h standard, and relatively few (in the lower right quadrant) that violate the 1-h standard while meeting the 8-h standard. In addition, those points which would not attain the 8-h standard are those points for which the 1-h ozone is not much higher than the 8-h ozone, so those points are likely to have relatively high background ozone levels and be relatively insensitive to local emissions reductions.

The situation for ozone pollution control is not as grim as it first appears, though, because most pollution controls will operate continuously or daily, so that most days will have ozone levels well below the 1-h standard when Houston is in compliance with it. A fixed reduction of ozone so as to bring the 0.190 ppmv points into compliance will have the effect of bringing most days with lower ozone levels into compliance at the same time. Additionally, the difference in the definitions of the 1-h and 8-h ozone standard means that more exceedances are tolerated in the 8-h standard. The scatterplot (Fig. 13) is not conclusive one way or the other, so it appears that only photochemical modeling can determine whether controls for 1-h exceedances would bring Houston into compliance with the 8-h standard.

5. Statistical Relationships Between Meteorological Factors and Ozone Concentrations

In Part I, correlations between 8-h ozone levels and various meteorological variables were presented. The strongest correlations are reproduced here in Table 3 and the complete list of variables is reproduced here in Table 4. All of the correlations presented here are significant at the 99% confidence level.

Table 3: Strongest meteorological correlations with ozone.

Houston Background	**Correl.**	**Houston Local**	**Correl.**
cosD1	.578	tmp0	.478
v1	-.538	spd0	-.358
cosD2	.501	binpt0	-.335
v0	-.483	binp0	-.320
cosD0	.469	binp6ht0	-.314
v2	-.445	spd1	-.304
isS0	-.391	u1	.276
isS1	-.391	binp6h0	-.294
spd0	-.384	u2	.231
spd1	-.372	u0	.219
isNE1	.358	sinD2	-.200
isNE2	.315	isSW1	.193

The strongest correlations with background ozone levels are with the cosine of wind direction (cosD), the north-south component of the wind (v), and a binary indicator of a

Table 4: Variables included in the statistical analysis. The "" can be 0, 1, or 2 and represents the number of days prior to the ozone event. The primary variable types are binary (B) and continuous (C).*

Variables Included in the Analysis

ID	Definition	Type
u*	u-component 12 LST wind day [0, -1, -2]	C
v*	v-component 12 LST wind day [0, -1, -2]	C
spd*	Wind speed day [0, -1, -2]	C
dir*	Wind direction day [0, -1, -2]	C
tmp0	Temperature on day 0	C
cosday	Cosine of day of year	C
pday0	Precipitation on day 0	C
binp0	If precipitation ≥0.01" on day 0	B
binpt0	If precipitation (≥Trace) on day 0	B
p6h0	Precipitation 06-12 LST day 0	C
binp6h0	If precipitation ≥0.01" 06-12 LST day 0	B
binp6ht0	If precipitation ≥Trace 06-12 LST day 0	B
daywk	Day of the week	*
ismon	If day is Monday	B
istue	If day is Tuesday	B
iswed	If day is Wednesday	B
isthr	If day is Thursday	B
isfri	If day is Friday	B
issat	If day is Saturday	B
issun	If day is Sunday	B
isN*	If wind is from N on day [0, -1, -2]	B
isNE*	If wind is from NE on day [0, -1, -2]	B
isE*	If wind is from E on day [0, -1, -2]	B
isSE*	If wind is from SE on day [0, -1, -2]	B
isS*	If wind is from S on day [0, -1, -2]	B
isSW*	If wind is from SW on day [0, -1, -2]	B
isW*	If wind is from W on day [0, -1, -2]	B
isNW*	If wind is from NW on day [0, -1, -2]	B
sinD*	Sine of wind direction on day [0, -1, -2]	C
cosD*	Cosine of wind direction on day [0, -1, -2]	C

due south wind (isS), on days that lead the background ozone day by 0, 1, or 2 days. All of these correlations are consistent with the wind patterns identified in Part I as being associated with high levels of ozone. Specifically, they indicate the primary importance of wind from the continent leading to high levels of background ozone.

The strongest correlates with the local contribution to ozone have little in common with the strongest correlates with background ozone, thus supporting the division into background ozone and local contribution and the need to understand the separate meteorological causes of each. The temperature at zero lag (tmp0), for example, has the strongest correlation with the local contribution to ozone of any variable, but its correlation with background ozone is only 0.08 and is not statistically significant. The strong correlation with local contribution and weak correlation with background ozone may be partly causal, but it is may also be related to the climatological maximum in local contribution nearly coinciding with the warmest period of the year while the background ozone peaks in a transitional season.

The wind speed is strongly negatively correlated with both background ozone and local contributions. The strong interaction with local contribution is related to local stagnation, while the strong interaction with background ozone likely applies to the other end of the spectrum: strong winds imply air masses with short residence times over upstream pollution sources.

Local contributions are negatively correlated with various indicators of precipitation. The strongest negative correlation occurs with a binary indicator of a trace or more of precipitation over 24 hours with lag 0 (binpt0). Negative correlations are also found with measurable precipitation (excluding a trace) (binp0) and precipitation over a six-hour period during daytime, excluding (binp6h0) or including (binp6ht0) a trace.. Rain (and associated clouds) are a severe detriment to local contributions to ozone. They are also a significant detriment to high background ozone levels (not shown), but the correlation is not as strong as with the variables shown in Table 3.

The most significant remaining correlate with local ozone contributions is the east-west component of the wind, such that a component from west to east is positively correlated with local ozone contributions. The enhancement of local ozone by an eastward wind takes place exclusively at low west-east wind speeds, so it may be caused by an interaction with the sea breeze cycle (see the next section) that leads to stagnation in early afternoon if the mean wind is weak from the west.

Many of the factors appearing in the correlation analysis are in turn correlated with each other. In order to discern the independent relationships between high ozone and the various parameters, a stepwise regression was performed relating these factors to both the background and local contribution of ozone. Factors were added to the model, and subsequently kept, until all the factors in the model were significant at the .10 level and none of the factors outside the model were significant at the .10 level. The results of this regression suggest which (among the groups of correlated factors) are the most relevant to predicting ozone levels.

For background ozone, 14 predictors were identified as being significant to predicting background ozone levels (Table 5). Nine of these pertain to winds and three pertain to precipitation, making these two meteorological features the most important to explaining background ozone concentrations. Temperature makes sense for the same reasons that temperature relates to the local contribution to ozone, though it is not as critical to background ozone levels. The cosine of the day of the year, the last predictor, has a curiously negative significant relationship with background ozone. When considering that this analysis consists only of warm season data, however, this relationship makes sense due to the double-peak distribution of background ozone levels in Houston.

Table 5: The most important correlates with background ozone, as estimated through stepwise regression. The order in which the variables were added to the regression model, their p-value (1 – confidence), and the sign of their correlation are indicated.

Added	**Factor**	**p-value**	**Correl.**
1	cosD1	<.001	+
2	spd0	<.001	-
3	binp0	<.001	-
4	cosD2	<.001	+
5	u0	<.001	-
6	isW1	<.001	+
7	tmp0	<.001	+
8	cosD0	<.001	+
9	isNE0	0.004	-
10	binp0t	0.002	-
11	p6h0	0.042	-
12	spd1	0.068	-
13	v1	0.003	+
14	cosday	0.076	-

For local contribution, the stepwise regression identified a model consisting of 11 factors, many of which have already been identified as relevant to the local contribution of ozone. These factors, their significance, and their relationship to local contribution of ozone (positive or negative) are listed in Table 6, in the order they were added to the model.

Table 6: Most important correlates with local contribution to ozone. Information as in Table 5.

Added	**Factor**	**Sig.**	**Correl.**
1	tmp0	<.001	+
2	spd0	<.001	-
3	binpt0	<.001	-
4	isNE0	0.018	-
5	sinD0	0.005	+
6	isSW1	0.020	+
7	issun	0.029	-
8	spd1	0.033	-
9	spd2	0.002	+
10	isE1	0.040	-
11	binp6h0	0.083	-

The temperature, speed, and precipitation contributions to local contribution have already been discussed. It is worth noting that two precipitation terms made the final cut, stressing the importance of precipitation as a negative binary predictor of locally generated ozone. Other results of interest include the binary predictors of wind direction (NE and E negative and SW positive) and the binary factor of whether it is Sunday. It is speculated that the correlations with the binary wind directions, as well as the positive correlation with the two-day lag wind speed, may be due to advection of photochemical reactants into the Houston area. The Sunday binary makes sense since anthropogenic emissions sources should be at a minimum on Sundays. The Sunday binary was not significant in the ordinary regression presented in Table 3, but it shows up in the stepwise regression because other important meteorological variables, which may randomly have been more or less common on a Sunday over the six-year period, have been controlled for.

In summary, the statistical correlations illustrate the importance of transport for high background levels of ozone, with day-to-day stagnation also being of potential importance. For local contributions, warm temperature, clear skies, and light winds are key. There is not much surprising in these results, so the next chapter will consider the role of Houston's local wind patterns in generating 8-h ozone exceedances.

6. The Relationship Between 8-h Ozone and Winds

6a) The Observed Diurnal Wind Cycle

Extensive work on the 1-h ozone standard has demonstrated the importance of the peculiar wind patterns in Houston on the formation of high concentrations of ozone. In particular, profiler and buoy data from TexAQS-2000 showed that the wind tends to vary in a circular or elliptical fashion throughout the day.

Figure 14 illustrates this wind pattern using data from a two-week period in late August 2000, during the TexAQS-2000 field program. The vector average (resultant) winds were strongest between midnight and dawn, during which period they blew from south to north. The weakest winds occurred during the afternoon.

The dominance of this elliptical rotation of the wind vector is attributable to the proximity of Houston to the critical latitude of 30 degrees north, at which the daily heating and cooling cycle is in resonance with the inertial period. Although the relevance of linear theory of the sea breeze to the real atmosphere is uncertain, the theory does successfully predict that this elliptical sea breeze oscillation should have a very large horizontal scale.

This regular daily rotation of the wind, henceforth called the *sea breeze rotation*, is dynamically distinguishable from the more familiar sea breeze front. The sea breeze front forms along the coastline during light wind conditions and penetrates inland during the afternoon. Behind the sea breeze front is air that has recently resided over the relatively cool water.

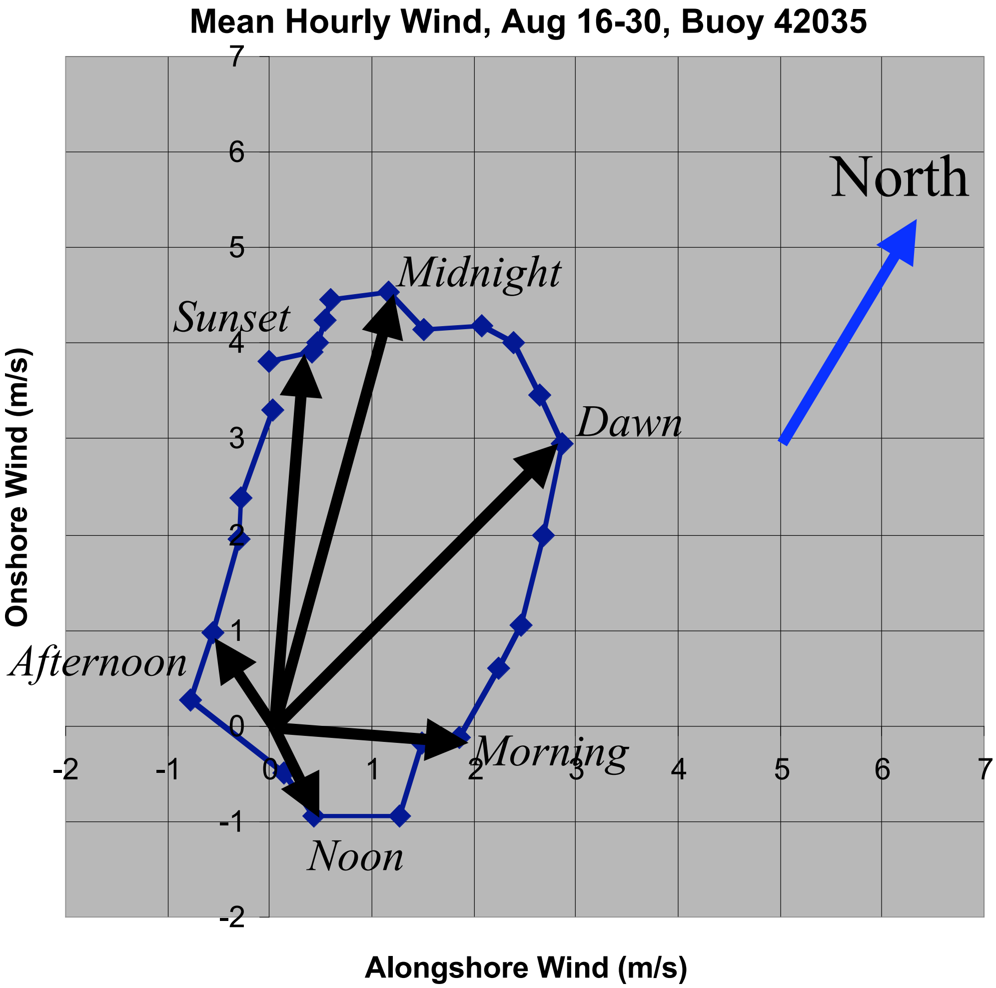

Figure 14: Hodograph of mean winds at a buoy offshore of Galveston during August 16-30, 2000. Winds averaged strong from the south-southeast near midnight and weak from the west around noon.

In contrast, the sea breeze rotation takes place nearly simultaneously not just at the coastline but also well inland and well offshore. The tendency for onshore flow that develops during the afternoon does not necessarily mark the arrival of marine air. Instead, it is possible for some inland locations to experience this sea breeze rotation, including a period of moderate onshore flow, without ever experiencing a marine air mass.

A similar wind pattern was detected by the radar wind profilers during TexAQS-2000. Figure 15 shows such a pattern from the profiler at Liberty Municipal Airport, located northeast of Houston. The wind pattern is a bit stronger, but the same basic

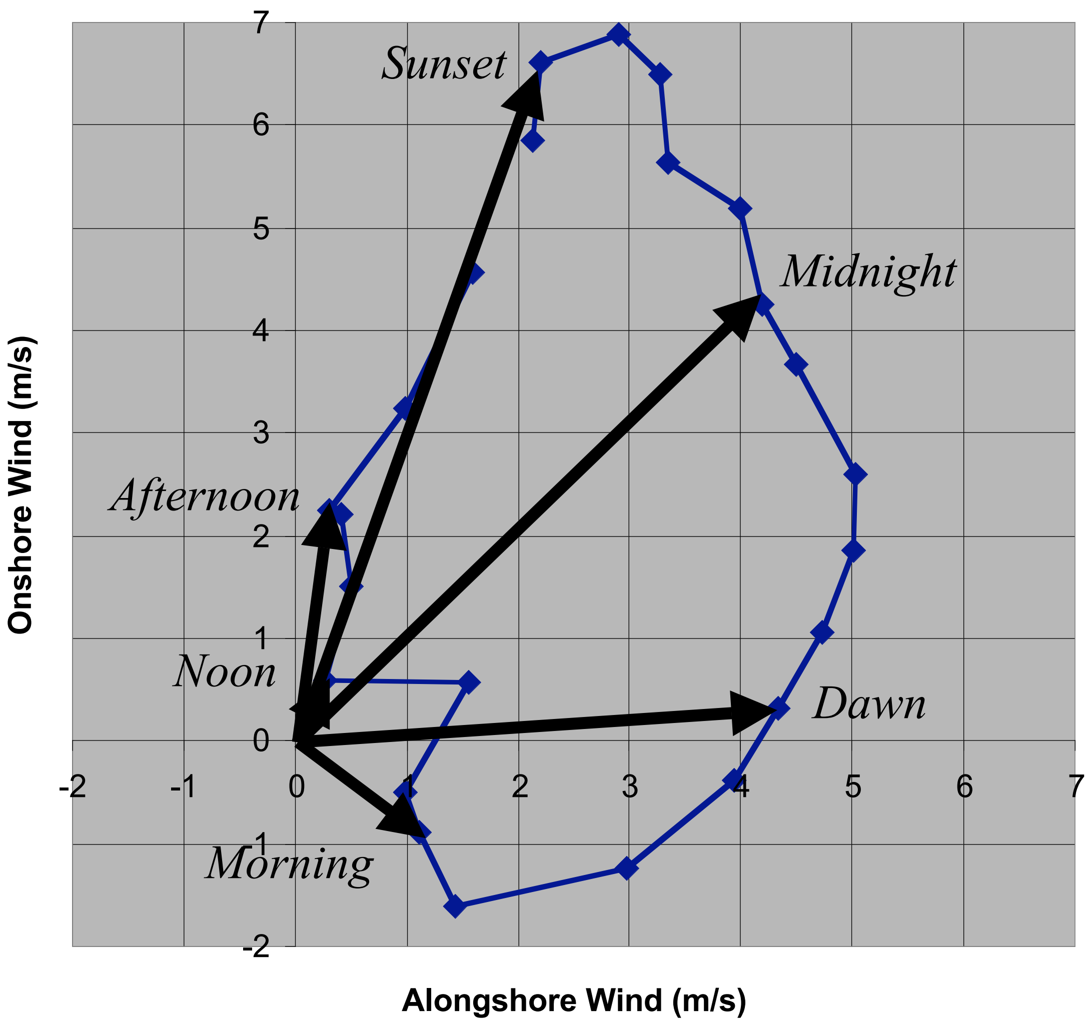

Figure 15: Hodograph of mean winds at the Liberty wind profiler, 247 m above sea level (225 m above ground level), August 16-30, 2000.

structure is apparent: a steady, elliptical clockwise rotation of the wind vector throughout the day and night. The radius of the ellipse traced by the wind is about 2-4 m s^{-1}.

Unfortunately, the extensive surface meteorological network in the Houston area is not particularly useful for detecting this wind pattern. At night, winds become calmer as the air becomes more stable and friction becomes more important. Thus, the strong onshore winds in the evening are rarely felt at the surface through most of Houston. The winds at C1 (Fig. 16) are illustrative. From morning through afternoon they are similar to the winds at Liberty, but starting shortly before sunset the mean winds become progressively weaker and weaker until becoming nearly calm after midnight. After sunrise the boundary layer deepens and winds become stronger, at least temporarily.

6b) Diurnal Wind Cycle Schematics: The Circle Model

A series of schematic diagrams illustrates how the daily wind patterns will evolve, given the 24-hour mean wind. In Figure 17, the rim of the sun represents the approximate circle that the wind vector traces on a hodograph, as plotted in Figs. 14 and 15. A set of wind vectors drawn from any arbitrary point in the diagram to the rim of the sun depicts the variation of the wind throughout the day and night for a particular 24-h mean wind speed and direction. If the 24-h mean wind is zero, the origin point would be the center of the sun and the actual wind would represent a pure rotation. In Fig. 17, the mean wind is taken to be weakly from the south-southeast, and the wind vectors are drawn from a point southeast of the origin. Rather than being constant in magnitude as they would be if the mean wind were calm, the schematic diagram illustrates that the strongest wind will be from the south-southeast and would occur (above the ground) late in the evening.

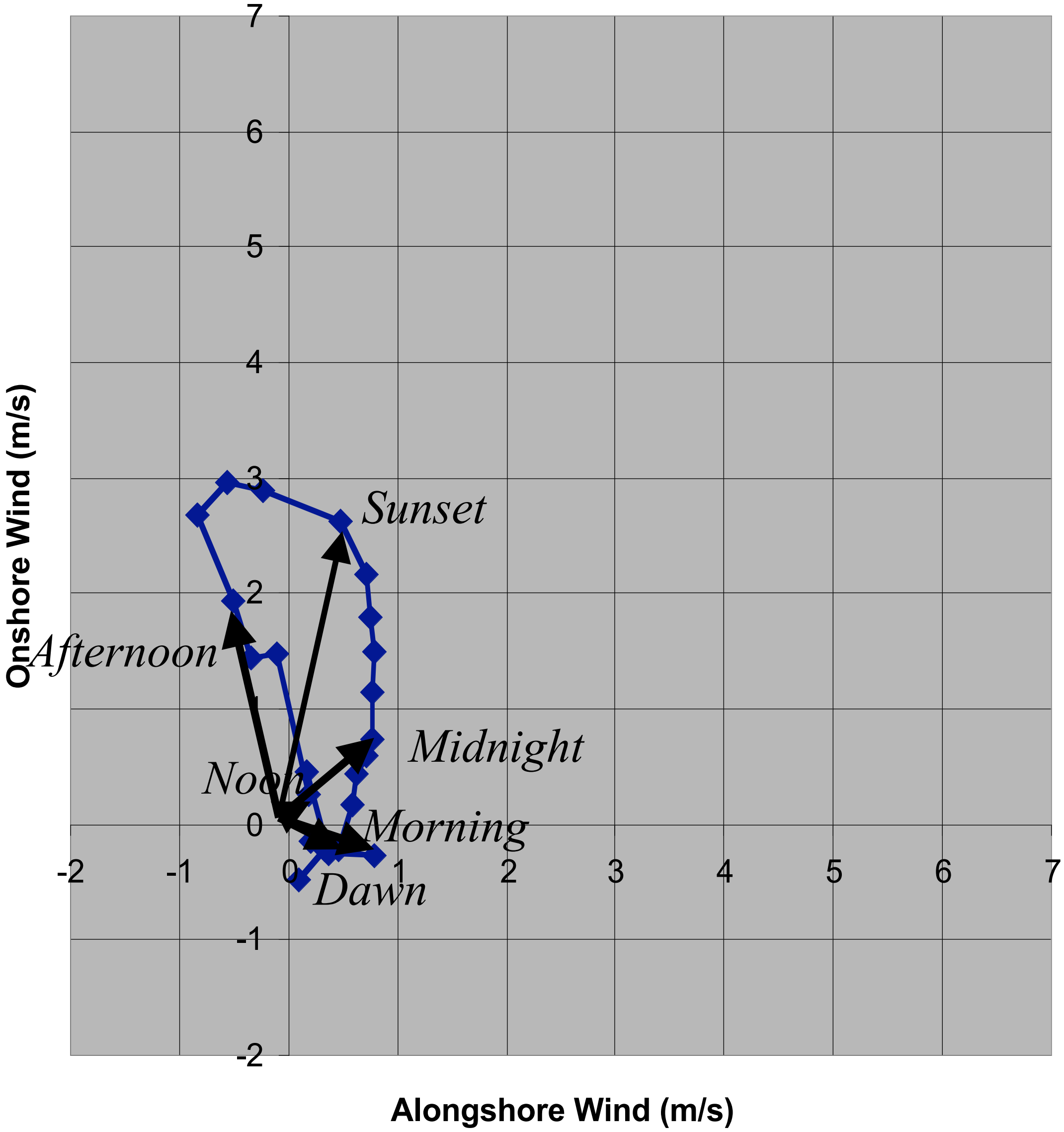

Figure 16: Hodograph of mean winds at C1 (Houston East), August 16-30, 2000. Winds become progressively calmer shortly before sunset as the boundary layer becomes stable.

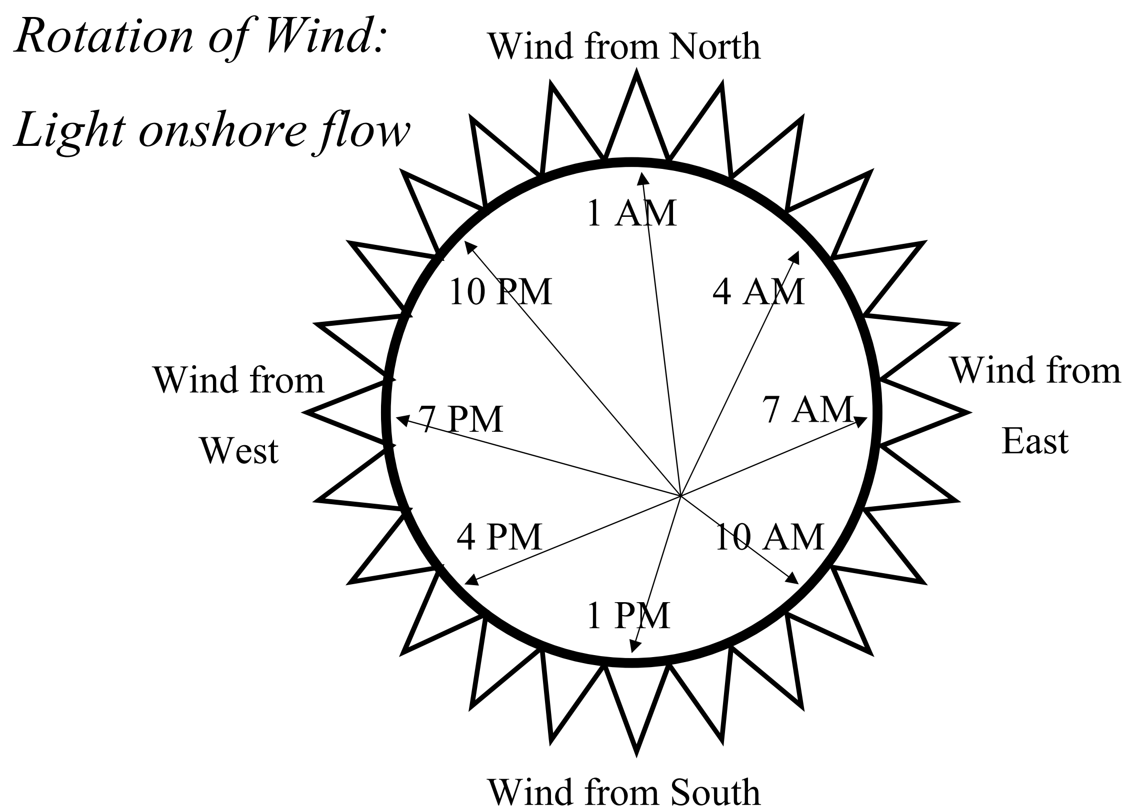

Figure 17: Schematic diagram showing the idealized circle traced by the low-level vector wind under very light southeasterly wind conditions.

around midnight, and that the wind will almost rotate perfectly with little change of wind speed. Note that the average resultant wind from about 4 AM to 7 PM is zero. This means that air parcels will return to their 4 AM location at 7 PM, suggesting a double dose of emissions into the air. If the circle is taken to have a radius of 6 mph, which is common for the sea breeze rotation in this area, wind speeds would be less than 2 mph between about 9 AM and 1 PM, enhancing the concentration of pollutants in the local atmosphere.

Rotation of Wind:

Moderate flow

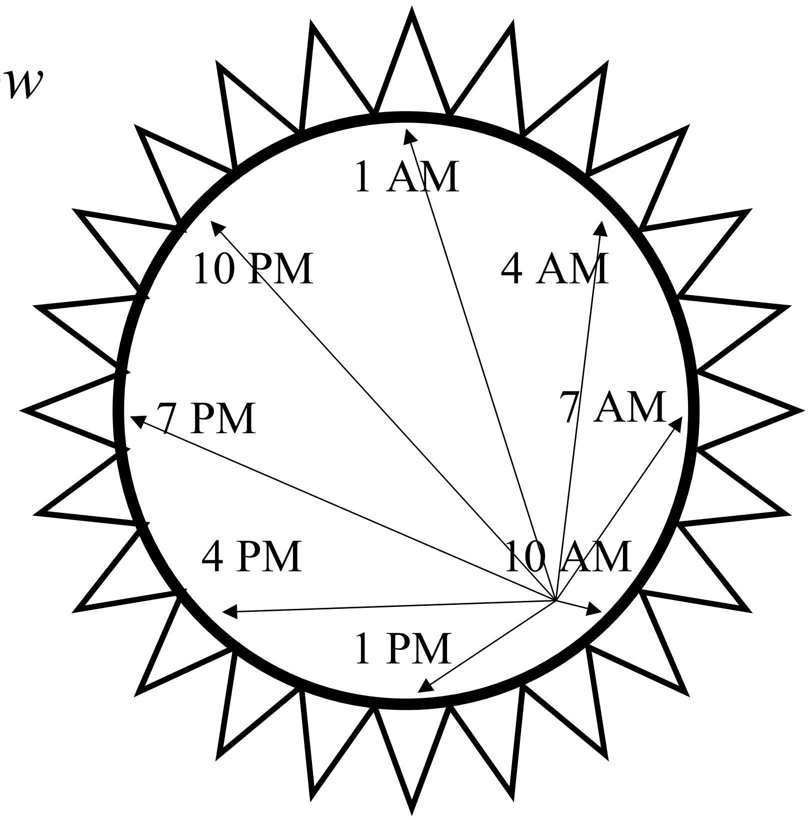

Figure 18: Schematic diagram showing the idealized circle traced by the low-level vector wind under moderately weak southeasterly wind conditions.

In Fig. 18, the southeast wind has been increased somewhat, so that they are nearly equal to the magnitude of the sea breeze rotation. Now the winds become nearly calm around 10 AM, and recirculation takes place between 7 AM and 1 PM. Such a wind pattern would favor particularly high concentrations of pollutants due to the stagnation and double dosing.

Finally, Fig. 19 shows moderate southeasterly winds. No recirculation nor stagnation take place. Relatively low levels of pollution would be expected with this scenario.

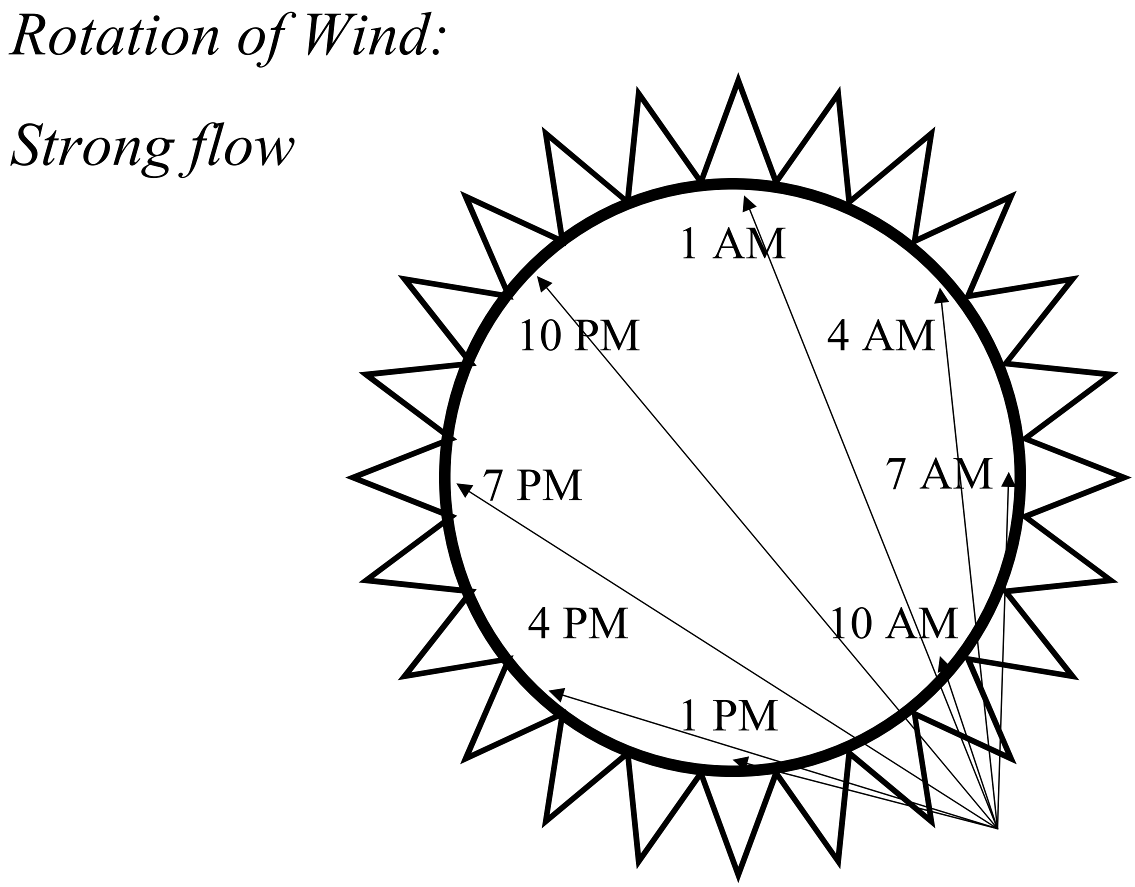

Figure 19: Schematic diagram showing the idealized circle traced by the low-level vector wind under stronger southeasterly wind conditions.

In Figs. 17 and 18, the time of stagnation depends on the resultant average wind direction. While a southeast wind produces stagnation in the morning, a southwest wind would produce stagnation in the afternoon. A northeast wind might be expected to produce stagnation at night, so the impact of the sea breeze rotation may not be as large under northeast wind conditions as it is under onshore wind conditions.

In summary, the circle model predicts high local contributions of ozone when wind speeds are less than or equal to the sea breeze rotation amplitude, and low local contributions of ozone when wind speeds are stronger.

6c) Ozone, Wind Speed, and Wind Components

The actual dependence of ozone levels in Houston on wind speed is given in Fig. 20. The average 1-h maximum ozone does become substantially higher below 4 m/s (8 mph), when recirculation can take place. Ozone levels steadily decline with increasing wind speed up to 9 m/s (16 mph).

The breakdown of the 1-h maximum ozone into background ozone and local contributions (also shown in Fig. 20) shows that the low wind plateau effect appears almost entirely in the local contribution to 1-h ozone, which averages 0.065 ppmv at wind speeds from 0 to 4 m/s (8 mph). The local contribution steadily declines at higher wind speeds.

Stagnation sufficient to produce recirculation of pollutants from day to day is favorable for high background levels of ozone. The brief stagnation periods when the large-scale wind nearly matches the sea breeze rotation amplitude, while favorable for short-term, localized ozone generation, do not directly enhance the background. Thus there is no plateau effect and background ozone levels decline fairly rapidly toward a steady value near 5 m/s (9 mph).

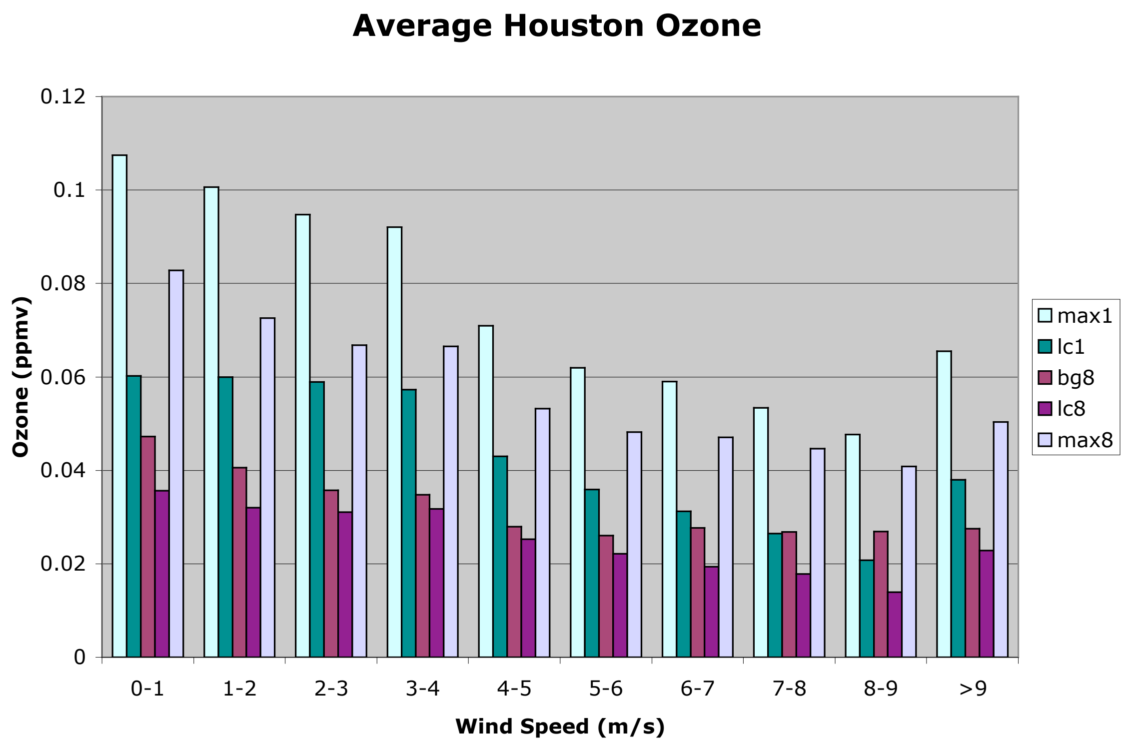

Figure 20: Maximum 1-h ozone, local contribution to 1-h ozone, background ozone, local contribution to 8-h ozone, and maximum 8-h ozone in the Houston region, as a function of resultant vector wind speed at buoy 42035, May-Sept., 1998-2003.

The 8-h ozone levels depend on the same background values. The local contribution to 8-h ozone levels does not have quite as strong a threshold dependence on wind speed as the local contribution to 1-h levels. This reduced dependence on the exact wind speed is perhaps because a broad area of fairly high ozone concentrations can be just as effective a contributor to an 8-h ozone maximum as a localized area of very high ozone that only remains over a particular monitor for a short time.

The correlations of meteorological factors with background ozone from Part 1 (Nielsen-Gammon et al. 2005) indicate that wind speed is not as good a predictor of background ozone levels as the north-south component of the wind. To help examine

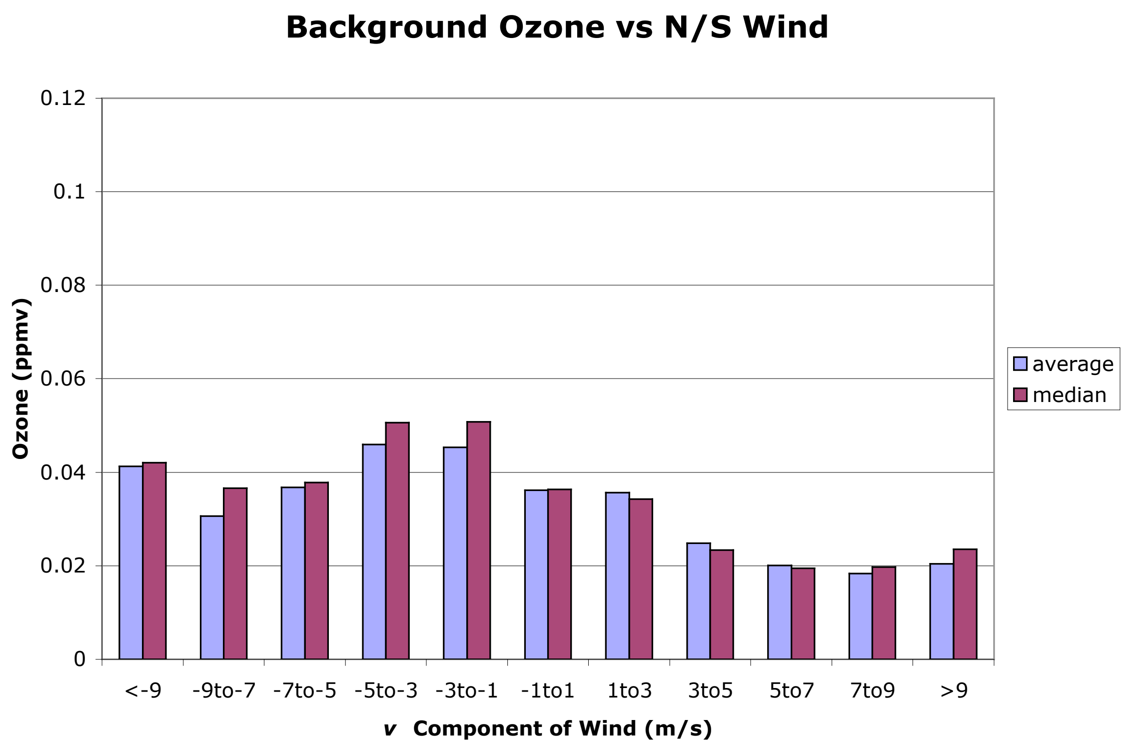

Figure 21: Background ozone as a function of the north-south component of the 24-hour resultant vector wind speed at buoy 42035, May-Sept. 1998-2003. Positive winds are from south to north.

this relationship, Fig. 21 stratifies background ozone by the magnitude of the north-south component of wind. While there is a negative correlation, the relationship is not linear, and the largest background ozone levels occur with a wind component from the north of 1-5 m/s (2-9 mph). In addition to average background ozone, Fig. 21 also shows median background ozone. Although the average ozone levels in the ranges –7to-5 and 1to3 are similar, the median is higher at –7to-5 and lower at 1to3. Thus, for the weak southerly winds, most background ozone levels are fairly low but with a few high outliers, but for moderate northerly winds, most background ozone levels are fairly high but with a few low outliers.

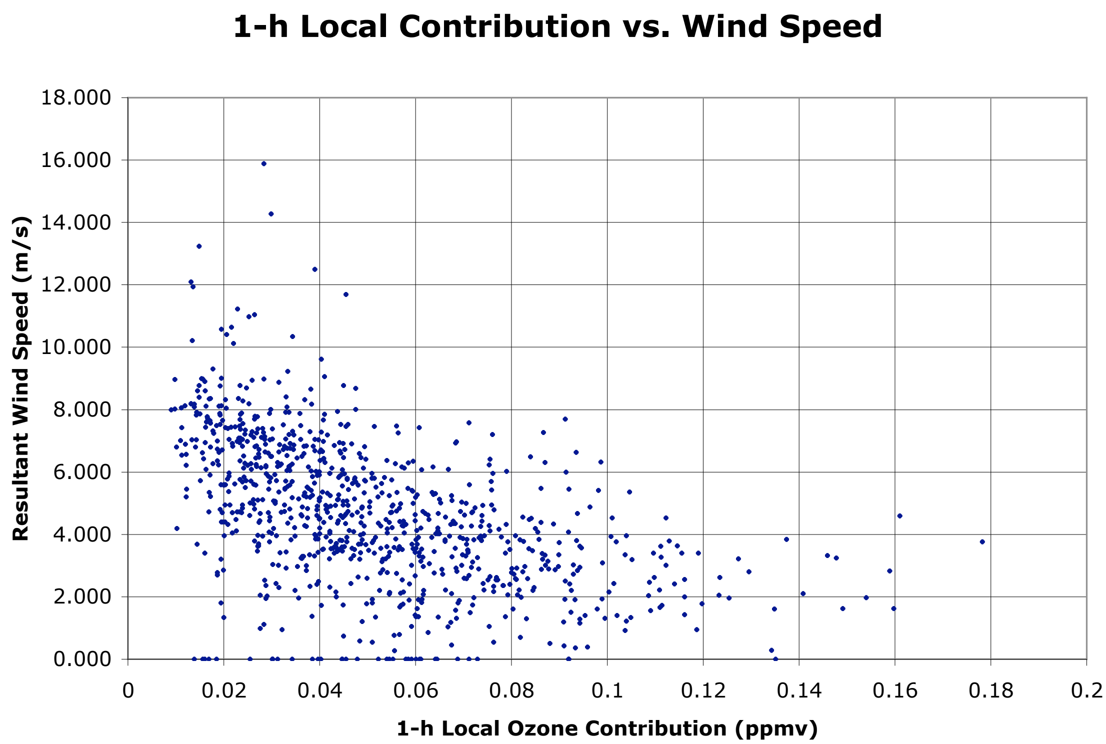

Figure 22: Local contribution to 1-h ozone in Houston and its dependence on mean resultant wind speed, May-Sept., 1998-2003. Points along zero wind speed axis indicate missing wind data.

While one can hope that these dependencies on wind speed have predictive value, scatterplots of ozone versus winds indicate otherwise. The situation is best with the 1-h local contribution, shown in Fig. 22. The lighter wind speeds, in addition to implying higher average local contributions, are required for local contributions greater than 0.120 ppmv. Furthermore, it can be seen that, while the average value of local contribution is nearly uniform at low wind speeds (Fig. 20), the exceptionally high ozone levels are not favored at mean wind speeds less than 1 m/s (2 mph). This apparently counterintuitive result is explained by means of Fig. 17: a resultant mean wind speed of 1 m/s implies that because of the sea breeze rotation the wind is always at least 2 m/s. Very high 1-h local contributions require stagnation, and because of the sea breeze, local stagnation is not possible when large-scale stagnation is present.

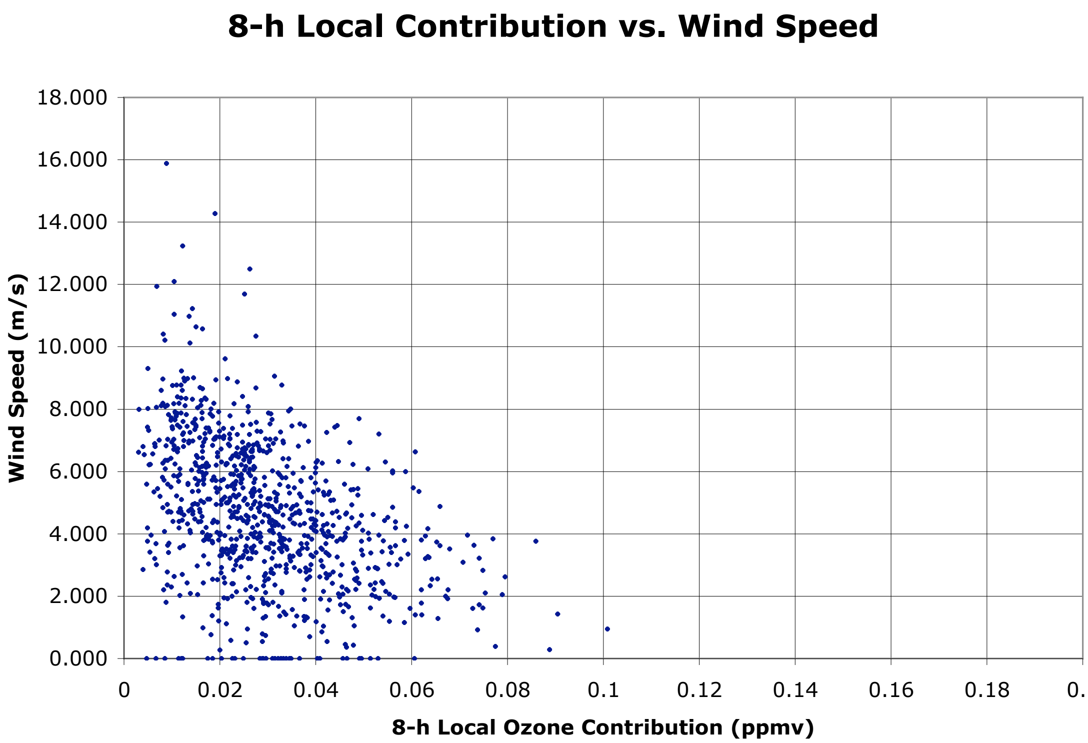

Figure 23: Local contribution to 8-h ozone in Houston and its dependence on mean resultant wind speed, May-Sept., 1998-2003.

Immediately obvious from Fig. 23 is that, unlike 1-h local contributions, 8-h local contributions almost never exceed 0.080 ppmv. In addition, the 8-h local contribution has unusually high values even at very low wind speeds. The lack of pure stagnation is not an obstacle to high 8-h local contributions. The strong negative correlation between local contributions and wind speed is accompanied by substantial scatter. The local contributions necessary for 8-h ozone design value days, approximately 0.040 ppmv, can be reached at almost any wind speed. It appears that other factors, such as variability in PBL depth, help to control the 8-h local contribution.

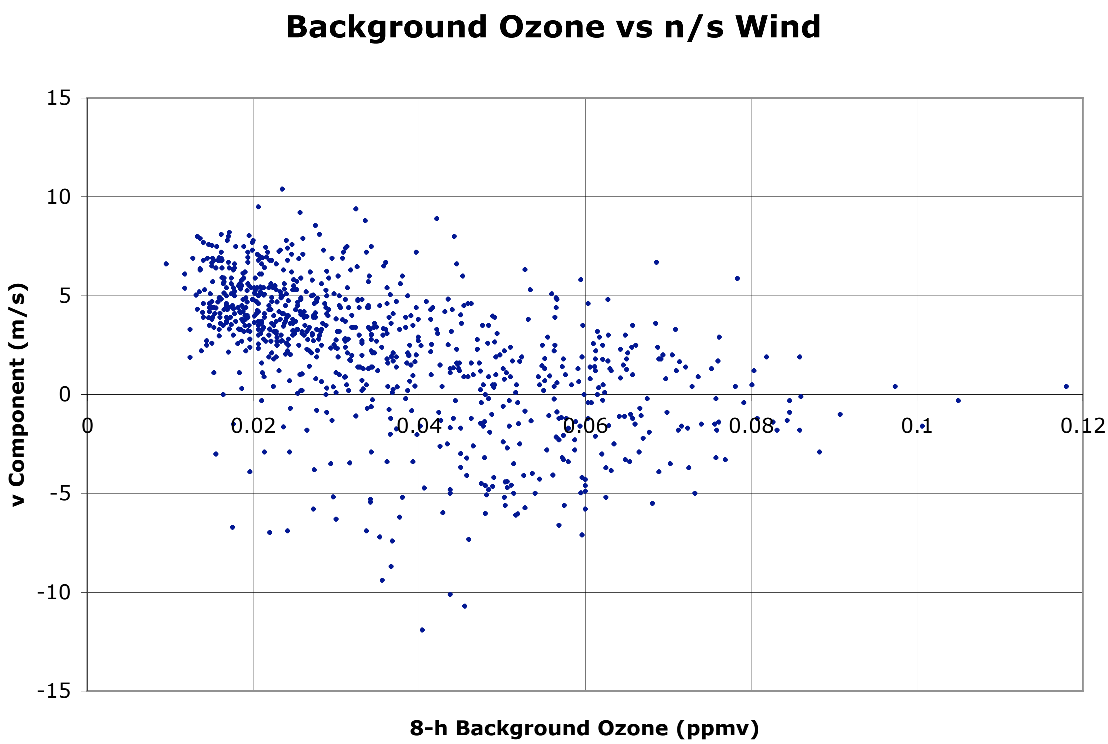

Figure 24: Scatterplot of dependence of 8-h background ozone on the north-south component of the resultant mean wind, May-Sept., 1998-2003. A wind component from the south is positive.

As noted earlier, the north-south component of wind is a better local predictor of background ozone than is the wind speed. In the scatterplot (Fig. 24), a strong asymmetry about v=0 is present, with moderate winds from the south corresponding to low background ozone and moderate winds from the north corresponding to high background ozone. The two points beyond 0.105 ppmv correspond to both very light *v* and very light *u*, such that the total resultant wind speed for that day is well below 1 m/s (2 mph). Apparently those two dates represent "perfect ozone storms", with the previous day's emission progressing in a circle under the influence of sea breeze rotation and arriving back in Houston just in time for peak ozone levels.

6d) Wind Scatterplots

With 1-h ozone, the most useful display of meteorological information was a scatterplot of various levels of ozone exceedances as a function of the 24-hour resultant mean large-scale wind as measured by the nearby buoy. Such a plot is reproduced here, but with the addition of 8-h exceedances (Fig. 25).

The reproduction of the 1-h exceedances shows that such exceedances are common at low wind speeds but can also occur at higher wind speeds when the wind is out of the southwest or northeast. Earlier work has attributed those exceedances to enhanced sea breeze rotation/stagnation and shallow mixing heights, respectively. The additional cases that are 8-h exceedances tend to expand the margins of the 1-h exceedance events.

Broken down into categories, a clearer picture begins to emerge. A similar plot of the 1-h local contribution (Fig. 26) indicates a strong preference for very high ozone when the mean resultant wind speed is about 2 m/s (4 mph) and the mean resultant wind direction is from the southeast, south, or southwest. This tendency is consistent with stagnation and recirculation taking place in late morning to early afternoon (see Fig. 18). An example of this sort of day was August 25, 2000, during TexAQS-2000. Stagnation

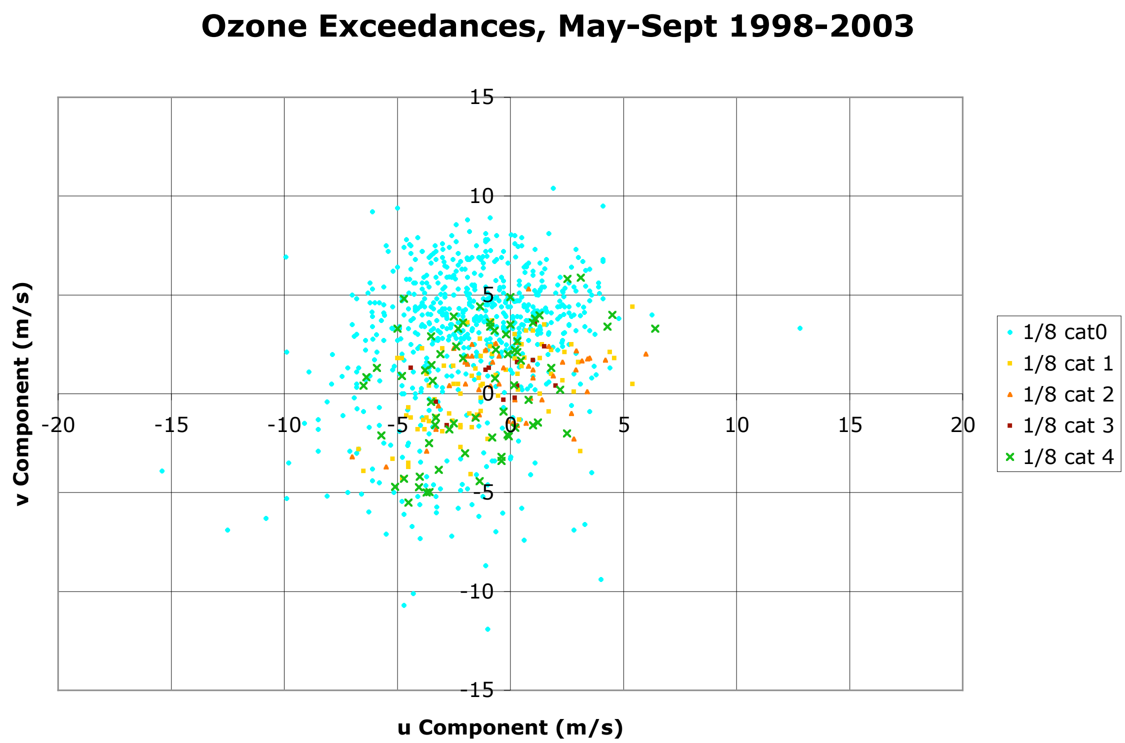

Figure 25: Ozone exceedances as a function of buoy resultant 24-hour mean wind, May-Sept., 1998-2003. Each dot represents an ozone level and is plotted at a point corresponding to the mean vector wind on that day. The wind vector can be reconstructed by drawing or imagining a vector starting at the origin and ending at the ozone level dot. Cat 0: no exceedances. Cat 1: 1-h ozone between 0.125 ppmv and 0.155 ppmv. Cat 2: 1-h ozone between 0.155 ppmv and 0.190 ppmv. Cat 3: 1-h ozone greater than 0.190 ppmv. Cat 4: 1-h ozone less than 0.125 ppmv but 8-h ozone greater than 0.085 ppmv.

took place in the morning, and winds then increased from the east and later the southeast, bringing a blob of high ozone across Houston. August 25 appears on Fig. 26 as a Category 3 local contribution day with winds of (u=-1.1 m/s, v=1.2 m/s).

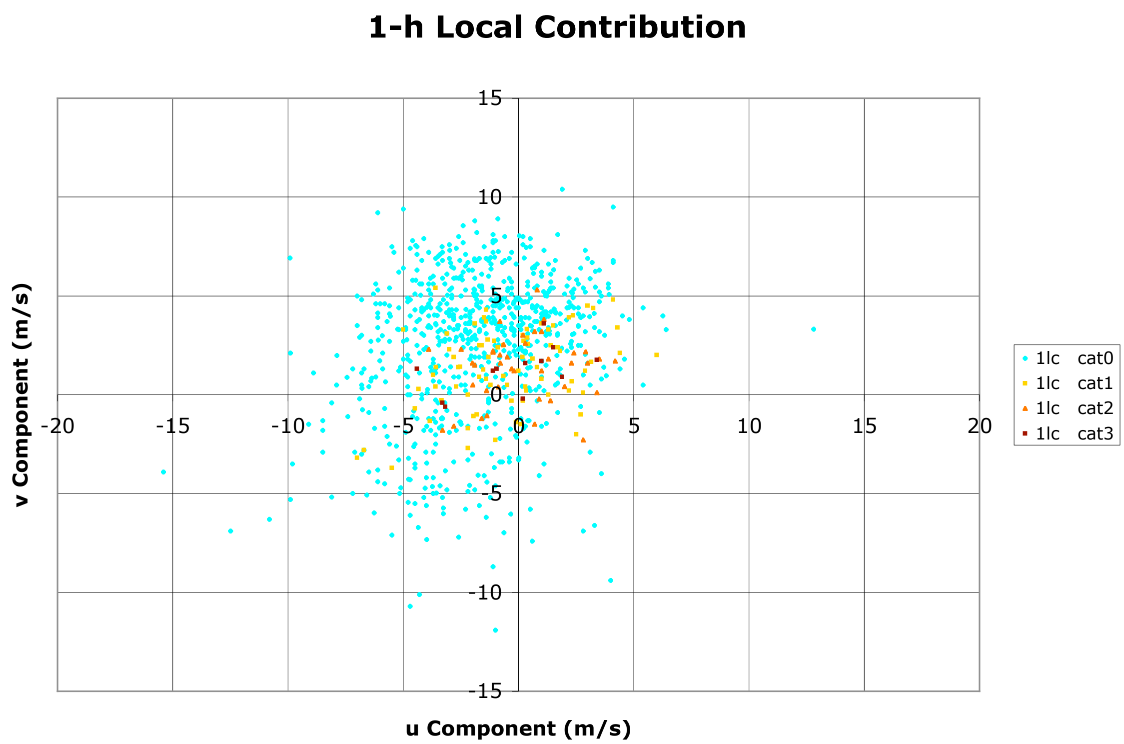

Figure 26: Ozone 1-h local contributions as a function of 24-h mean resultant buoy wind, May-Sept, 1998-2003. Cat 0: local contribution less than 0.080 ppmv. Cat 1: local contribution between 0.080 and 0.100 ppmv. Cat 2: local contribution between 0.100 and 0.130 ppmv. Cat 3: local contribution greater than 0.130 ppmv.

However, the tendency for stagnation to produce high ozone is not symmetric: winds from the north of 2 m/s (4 mph) do not produce high local contributions, even though stagnation should be just as likely. The reason for this, referring back to Fig. 18 again, is that the stagnation takes place at night, so the high concentration of ozone precursors has moved east and southeast before photochemistry can act to produce ozone. Such situations may therefore produce high levels of ozone on the east side of Galveston Bay, but no ozone monitors were present there during this period.

The propensity for high local ozone contributions extends to stronger mean winds from the west-southwest and from the east-northeast. Several of the former events took place during TexAQS-2000. An example is August 30, which appears in Fig. 26 as a Category 2 local contribution day with winds of (u=4.2 m/s, v=1.7 m/s). Analysis of that day determined that, because such a wind direction favors formation of a nocturnal coast-parallel low-level jet, the sea breeze rotation is unusually strong and local stagnation occurs in the afternoon even under relatively strong wind conditions. Furthermore, the rotation is such that polluted, stagnant air over Galveston Bay is brought back onshore.

Examination of events associated with winds from the east-northeast suggest that stagnation typically occurs from dawn to mid-morning, leading to a fairly early ozone peak before the daytime boundary layer has fully developed. One example of this type of event was Sept. 18, 2000, which appears in Fig. 26 as a Category 3 local contribution day with winds of (u=-3.3 m/s, v=-0.4 m/s). So in all the major local contribution cases, it appears that the meteorological pattern and sea breeze rotation combine to produce local stagnation in the Houston area sometime between 7 AM and 4 PM.

The other component of 1-h exceedances (and 8-h exceedances as well) is the background ozone. Part I showed that background ozone levels depend primarily on the larger-scale advecting wind patterns over the previous few days, bringing polluted air from the central and eastern United States. The dependence on the current day's local wind should be weak, but examination of that dependence will be useful for understanding the local conditions associated with high ozone levels overall.

The scatterplot for background ozone is presented in Fig. 27. Indeed, the high background ozone events have more scatter than do the high local contribution events. Nevertheless, because weather patterns change relatively slowly during the summertime, there is a strong tendency for high background ozone with winds from the northeast even on the day of the event.

The largest cluster of extreme background ozone events is found when the 24-hour mean winds are 0.5 m/s (1 mph) or less. Under such conditions, the ozone plume from Houston on a given day would follow a circular path and end up back in Houston on the following day. One example of such a day is August 30, 1999, which appears in Fig. 27 as a Category 3 day with (u=0.2 m/s, v=-0.3 m/s). During the afternoon of August 29, stagnant conditions were followed by winds from the south and southwest. Overnight, winds continued to veer, and were from the northwest and north after midnight. By morning of the next day, winds were from the northeast, before becoming southeasterly later in the day. The advection of the Houston ozone plume from August 29 to the north-northeast was apparently followed by its return from the north-northeast on August 30.

It is interesting to note that winds during the day of August 30, 1999 were everywhere stronger than 2.5 mph, even though the 24-hour resultant wind speed at the nearby offshore buoy was less than 1 mph. The sea breeze rotation is responsible for the air continuing to move about during stagnant large-scale conditions. So while stagnant large-scale winds do not favor development of high levels of ozone from the current day's emissions, they favor development of high levels of ozone because the previous day's emissions are carried back over the city.

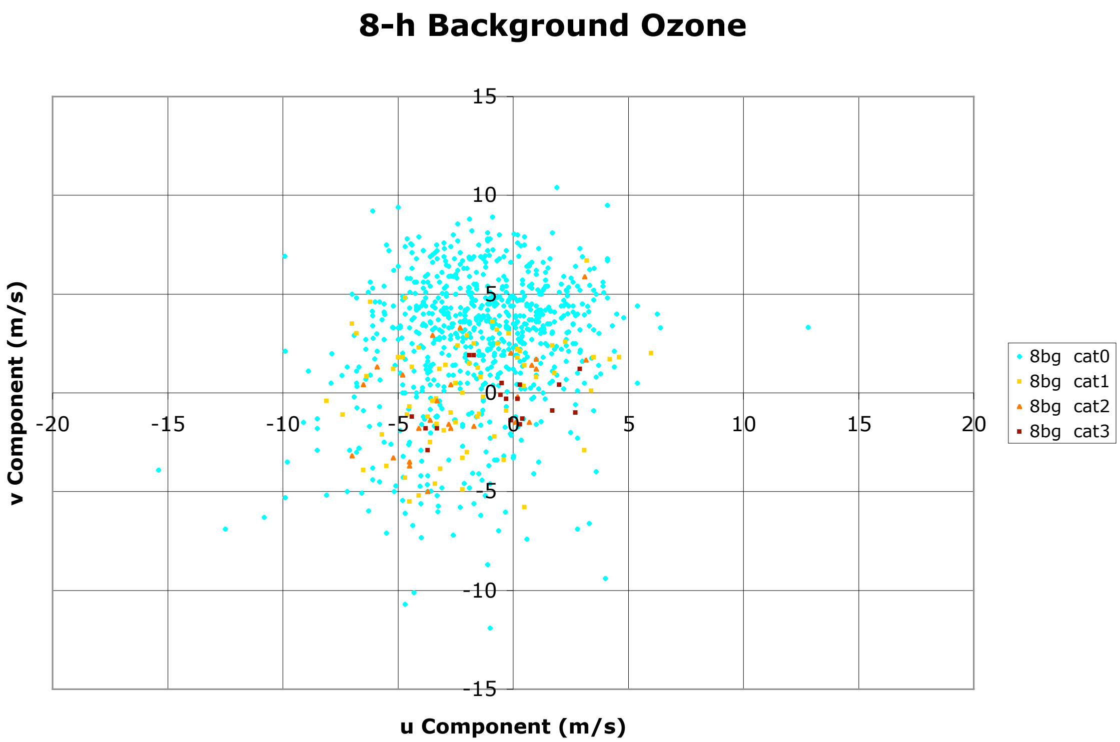

Figure 27: Background ozone concentrations as a function of 24-hour mean resultant buoy winds, May-Sept., 1998-2003. Cat 0: Background ozone less than 0.060 ppmv. Cat 1: Background ozone between 0.060 ppmv and 0.070 ppmv. Cat 2: Background ozone between 0.070 ppmv and 0.080 ppmv. Cat 3: Background ozone greater than 0.080 ppmv.

Explanations have been provided for high background ozone with large-scale winds from the northeast and large-scale stagnant winds, but very high background ozone with winds from the west-southwest seems a bit odd. Examination of those events reveals that they represent conditions in which the wind was blowing from the opposite direction on the previous day. The best example of this is May 29, 2003, which appears in Fig. 27 as a Category 3 point with (u=3.2 m/s, v=1.7 m/s). Ordinarily a moderate wind from the southwest would bring relatively clean air, but the 24-hour mean resultant wind on the previous day was almost precisely opposite: u=-3.3 m/s, v=-1.6 m/s. On May 28, the background ozone was 0.062 ppmv, and on May 29 it was 0.071 ppmv. It appears that the May 28 emissions from Houston partially combined with the preexisting high background ozone levels in a plume that was brought back over Houston on May 29 by a reversal of the large-scale wind direction.

The 8-h local contribution pattern (Fig. 28) is almost identical to the 1-h local contribution pattern (Fig. 26). Differences are subtle: the extremely high 8-h events are not concentrated about light winds from the south, but appear less regularly distributed,

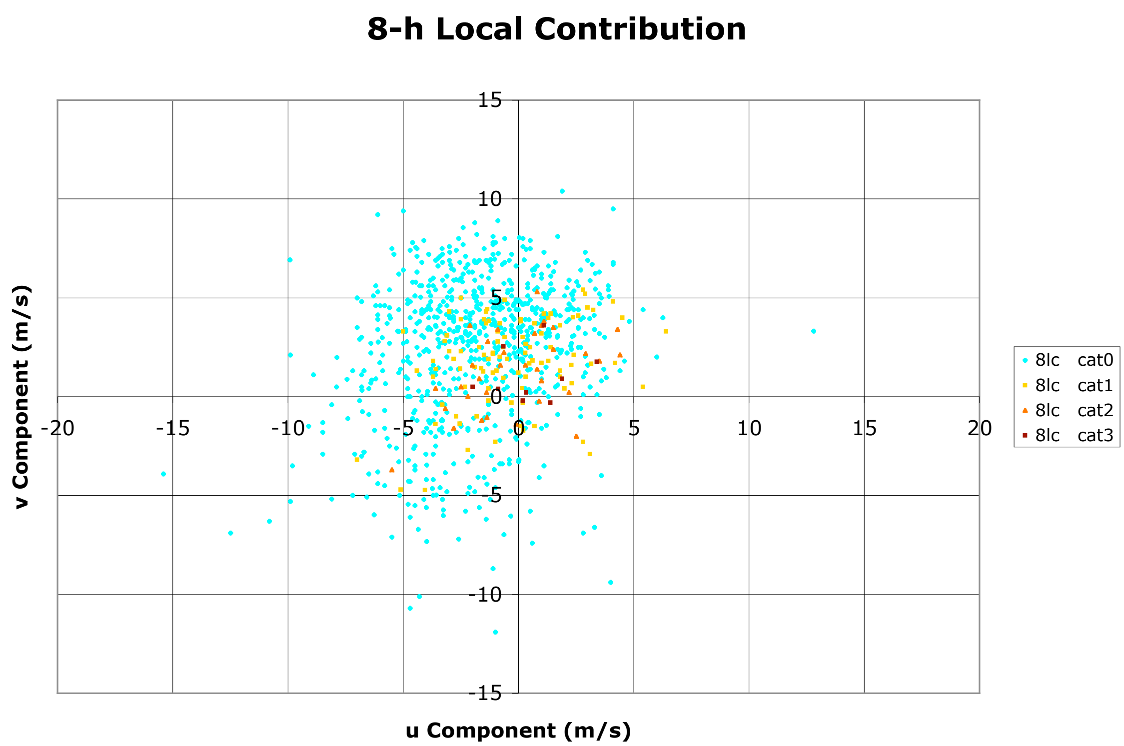

Figure 28: Ozone 8-h local contributions as a function of 24-h mean resultant buoy wind, May-Sept, 1998-2003. Cat 0: local contribution less than 0.045 ppmv. Cat 1: local contribution between 0.045 and 0.060 ppmv. Cat 2: local contribution between 0.060 and 0.075 ppmv. Cat 3: local contribution greater than 0.075 ppmv.

and moderately high 8-h events are relatively more common with moderate winds from the south (around 5 m/s, or 9 mph). As seen earlier when comparing local contributions to wind speeds (Fig. 20), moderately high 8-h local contributions are not nearly as sensitive to wind stagnation as are moderately high 1-h local contributions.

Finally, referring back to Fig. 25, the origins of the small differences between 1-h exceedance days and 8-h exceedance days have become apparent. The local contributions to 8-h exceedances can be substantial even without pure stagnation, because an elongated but fairly concentrated plume advecting over the same monitor for several hours is equally capable of producing a high 8-h local contribution. This is one reason that 8-h exceedances occur under a somewhat broader range of wind conditions than 1-h exceedances. The second reason is that 8-h exceedances are more dependent upon high background ozone levels. Because higher background levels of ozone are favored with winds from the northeast, the likelihood of an 8-h ozone exceedance is much greater than the likelihood of a 1-h ozone exceedance with moderate northeasterly winds.

Despite those differences, the basic relationships between high ozone and meteorological conditions remain fundamentally unchanged. The conditions favoring background ozone are, by definition, precisely the same. The conditions favoring high local contributions of ozone, be they 1-h or 8-h averages, are also very similar. The minor differences between the meteorological circumstances arise mainly because of the greater relative significance of background ozone levels in 8-h exceedances.

In addition to influencing the maximum concentrations of ozone, the winds, combined with emissions, determine the locations of the maximum ozone. Classical plume theory states that only a particular wind direction will lead to high levels of pollution from a particular source. In Houston, the spatial distribution of major sources makes it possible for a range of wind directions to lead to high ozone at a particular location.

Even if there was a single source for pollution, a broad range of 24-h mean wind speeds and directions would be expected to lead to high values of ozone at a particular point because the sea breeze rotation causes the actual wind to change considerably during the day. Furthermore, the concept of a regular rotation of the wind is a large-scale idealization, with differences from day to day and from place to place, depending on the sea breeze front and other local circulations. Thus, individual ozone events in Houston may depart significantly from the idealized patterns, but those patterns seem adequate for explaining the general conditions associated with most high ozone events in Houston.

7. Recommendations for Episode Selection and Modeling

Compliance demonstrations require confidence that the pollution reductions simulated by the photochemical model will apply to ozone exceedances in general. Because there is a greater number of 8-h exceedances than 1-h exceedances in the Houston area, episode modeling must consider a broader range of meteorological conditions.

Determination of the appropriate mix of episodes requires consideration of the circumstances that would lead to varying effects of emissions reductions. One obvious variable for the 8-h standard is the background ozone level. The effect of emissions reductions on a day with low background ozone and high local contributions to ozone would be expected to be quite different than the effects on a day with high background ozone and small local contributions. Therefore, modeled episodes should include both high background days and low background days.

One would also expect a difference in behavior between days with high remote background and days with high background because of the return of the previous day's emissions to Houston. The latter set of events includes the most extreme background ozone levels. It is possible that these "double-day" events will behave similarly to events with low background ozone, but the aging of the urban plume may change the importance of various chemical pathways. Such days may be difficult to simulate, because it is hard enough to get the 6-hour transport of an ozone plume correct, let alone the 30-hour transport of an ozone plume correct to a similar accuracy.

With 8-h events, which allow broader ozone plumes, there is likely to be greater interaction among emissions in various parts of Houston. It would be appropriate to consider events in which the Houston urban plume and Ship Channel plume mix and events in which they remain separate. The latter type of event is likely to occur when an ozone plume passes over Galveston Bay and returns to shore, producing exceedances along the coast of Galveston Bay or on Galveston Island. The photochemical processes with a plume trapped over the bay will also yield differences in ozone production.

Apart from the different trajectories of the ozone plumes and the differences in depths of the mixing layer, it is not obvious how difference in large-scale wind direction and the timing of stagnation would lead to critical attainment demonstration differences. Thus, it doesn't seem that high priority should be attached to ensuring that episodes involve exceedances at many different inland sensors.

The seasonal differences in background ozone suggest that both spring and late summer episodes should be considered. It is likely that both the biogenic mix and the ambient NOx levels will be different during those two periods. That these differences may have a significant impact in Houston is suggested by the ozone behavior at those stations with relatively few exceedances: exceedances were particularly rare in April, May, and June. Therefore it is clear that, at least locally, and possibly related to local sources versus ambient levels of NOx, the ozone in Houston during a springtime episode will behave differently than the ozone in Houston during a late summer episode. Since April-July exceedances are as common as August-September exceedances, both ozone regimes should be modeled.

To summarize, attainment demonstrations for the 8-hour standard should model a variety of high ozone days, including in order of priority: (1) high background and low background; (2) late summer background and springtime background; (3) second-day background and remote-origin background; and (4) high ozone over the Houston interior and high ozone advected onshore from Galveston Bay. If it is impractical to include all such alternatives, or if data is only available for a restricted number, the highest emphasis should be placed on the first of the two alternatives within each item on the priority list. Fortunately, most extended ozone events encompass much of the variability considered here. Also, if the model simulations encompass the above variability, it is not essential that there be a day-by-day correspondence to the specific event as long as the ozone formation scenarios are consistent with actual episodes.

Events to be modeled should not focus on the extreme events but rather events that yield (for example) the third to sixth highest annual ozone levels at particular stations. Because of the observed trends in background ozone versus local contributions, simulation of events with somewhat lower 8-h maximum ozone would also be appropriate if those events have high background ozone levels. If the present trends continue, events of this type will determine future 8-h ozone design values.

Based on the above considerations, the following ozone episodes are of possible interest for simulation for demonstration of compliance with the 8-h ozone standard, listed in order of priority:

August 3-11, 2004: Good variety and no extreme events in an extended episode.

May 23-31, 2003: An excellent springtime episode with a variety of wind conditions and background ozone levels.

Sept. 28-30, 2004: Widespread exceedances and very high background ozone levels that apparently did not include a previous day's contribution from Houston.

September 12-14, 2002: An extended episode of large-scale stagnation and likely self-contribution to high background ozone levels.

July 24-27, 2004: Strong flow from the northeast brings moderate remote background ozone to Houston.

Because the 8-h exceedances are somewhat less sensitive to wind than the 1-h exceedances, it is likely that accurate simulation of the wind field will not be as critical for attaining good photochemical model performance. Conversely, other factors, especially mixing heights, will attain greater importance for accurate simulations. Many 8-h ozone events occur with moderate winds, and under those conditions, compared to lighter wind events, the local contribution is less sensitive to the wind speed but remains just as sensitive to the mixing height.

References

Nielsen-Gammon, J. W., J. Tobin, A. McNeel, and G. Li, 2005: A conceptual model for eight-hour ozone exceedances in Houston, Texas. Part I: Background ozone levels in eastern Texas. Report to the Texas Environmental Research Consortium and the Texas Commission on Environmental Quality, 52 pp.